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Public Roads

A JOURNAL OF HIGHWAY RESEARCH

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THE BUREAU OF
PUBLIC ROADS,
U. S. DEPARTMENT
OF COMMERCE,
WASHINGTON

The practical capacity of this freeway in a suburban area is 3,000 passenger cars per hour in each direction

Public Roads

A JOURNAL OF HIGHWAY RESEARCH

Vol. 25, No. 10 *October 1949*

Published Bimonthly

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Practical Applications of Research

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In this issue of PUBLIC ROADS appears the first portion of an important work on highway capacity and its practical applications. The second half of the report, dealing with intersections at grade, weaving sections and unsignalized cross movements, ramps and their terminals, and the relation of possible and practical hourly capacities to annual average traffic volumes, will be presented in the next issue of PUBLIC ROADS. Thereafter, the report will be reprinted in its entirety as a manual on highway capacity.

Estimated motor-vehicle registrations, 1949 235

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The printing of this publication has been approved by the Director of the Bureau of the Budget January 7, 1949.

BUREAU OF PUBLIC ROADS

U. S. DEPARTMENT OF COMMERCE

E. A. STROMBERG, Editor

Highway Capacity:

Practical Applications of Research

BY THE COMMITTEE ON HIGHWAY CAPACITY
DEPARTMENT OF TRAFFIC AND OPERATIONS
HIGHWAY RESEARCH BOARD

Reported by
O. K. NORMANN, Chairman,
Chief, Section of Traffic Operations,
Highway Transport Research Branch,
Bureau of Public Roads

and W. P. WALKER, Secretary,
Highway Engineer,
Highway Transport Research Branch,
Bureau of Public Roads

Because a large part of the basic research and analysis upon which this study is founded was conducted by the Bureau of Public Roads, the Highway Research Board considers it fitting that the report be published by the Bureau of Public Roads. Much of the basic research has, indeed, already been published in PUBLIC ROADS magazine. But the cooperative efforts of the Bureau of Public Roads, the Highway Research Board Committee on Highway Capacity, and a large number of State, county, and city highway and traffic engineers have resulted in the amassment, from the length and breadth of the country, of a far greater assemblage of field observations than would have been possible under the aegis of a single organization. Without such a body of basic information, this report would have lacked the authority it holds. The text is largely the work of O. K. Normann and W. P. Walker, of the Bureau of Public Roads. The Committee members contributed valuable assistance, both in the review of fundamental concepts and in the preparation of text and illustrations.

A rational and practical method for the determination of highway capacity is essential in the sound economic and functional design of new highways and in the adaptation to present or future needs of the many existing roads and streets which must continue in use for extended periods of time. Basically, the subject concerns the effectiveness of various facilities in the service of traffic, and involves the many elements of highway design, vehicle and driver performance, and traffic control.

Highway capacity has been the subject of continuing study over a long period of years, and the literature in this field is extensive. Practically all consideration of the subject in the past, however, has been handicapped by insufficient breadth of scope and by lack of any considerable volume of accurate data.

The cooperative efforts of the Bureau of Public Roads, the Highway Research Board Committee on Highway Capacity, and many State, county, and city engineers, intensively applied in many places and for a number of years, have resulted in a great mass of field observations. Complicated and ingenious instruments have made feasible the collection of data in larger volume and greater accuracy than was heretofore possible, and have permitted the mechanical recording of information that could not otherwise be obtained at all.

The study has encompassed not only the capacities of rural highways with uninterrupted flow, which have been fairly well established in previous publications, but has undertaken to determine the capacities of intersections at grade, weaving sections, grade separations, and ramps, and the relation of hourly to annual average traffic volumes. Such information has never before been available in comprehensive form, particularly for urban facilities.

With such a broad base of fundamental data, and with such painstaking analysis of them, this study will undoubtedly be recognized as one of the most thorough in highway research history.

From this vast grist of basic facts, so minutely sifted and examined, far more than a work report has been produced. This document is truly a practical guide by which the engineer, having determined the essential facts, can design a new highway or revamp an old one with assurance that the resulting actual capacity will be as calculated.

HIGHWAY RESEARCH BOARD COMMITTEE ON HIGHWAY CAPACITY

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William P. Walker, *secretary*, Highway Engineer, Highway Transport Research Branch, Bureau of Public Roads.

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Introduction

HIGHWAY CAPACITY has been the subject of careful and painstaking study for more than three decades. Many able research men have made valuable contributions to the subject, which has increased in importance from year to year at a rate that probably parallels the rapid increases in traffic volumes and congestion on our streets and highways. The comparatively recent general acceptance of the importance of highway transportation in our national economy, and especially of adequate transportation facilities in our cities, where heavy traffic volumes require the construction of costly roadways, has greatly increased the need for reliable street and highway capacity information.

The primary reason for constructing streets and highways is to serve traffic, whether the traffic is local and originates along the particular street or highway, or whether its origins and destinations are in other areas. Basically, a study of highway capacity is a study of the effectiveness of the various facilities in serving traffic and involves the many elements of street and highway design, vehicle and driver performance characteristics, and traffic control measures which directly influence the movement of vehicles.

To be of value in the sound economic and functional design of new roadways, or in adapting to present or future demands many of the existing roadways which must continue in use for long periods into the future, the capacity criteria must include measures of such factors as speed and the relative interference between vehicles in addition to the number of vehicles that can pass a point on a given roadway in a specified period of time. It is of little value to know the quantitative measure without knowing the quality of service provided.

Previous Studies

The need for an authoritative presentation of facts concerning roadway capacity is illustrated in figure 1 and table 1, which show the capacity of a single traffic lane as published in a number of articles. Each source is similarly identified in both the figure and the table.

Nearly all of the curves or equations were calculated from the formula:

$$C=\frac{5{,}280V}{S}.$$

Where C=capacity of a single lane, in cars per hour.

V=speed, in miles per hour.

S=average distance in feet from center to center of vehicles.

In some cases the spacing between vehicles at various speeds was assumed to be a linear function of the speed, while in others the spacing was assumed to be a function of the square or some other exponent of the speed. In a few instances the spacing was based on very limited field observations and actual measurements. In general, however, spacings were arrived at by the use of such factors as driver reaction time, braking distances, and coefficients of friction.

Although some of these curves come remarkably close to showing the same relationship between speed and traffic volume as the curves presented in a following section of this report for specific roadway conditions, the wide range in vehicular volumes for any particular speed has had the effect of confusing rather than enlightening engineers who have made serious attempts to apply the results to practical problems.

Basis of This Report

One of the primary reasons that the earlier highway capacity analyses were not based on sufficient factual information was the lack of instruments to measure accurately and conveniently the vehicle speeds and the spacings between vehicles under normal operating conditions. The development of instrumentation for this purpose has progressed rapidly since 1934. Vital information pertaining to the actual driving practices of vehicle operators as related to other traffic on the highway and to the governing features of the highway itself can now be obtained for each individual driver, regardless of what the total traffic volume may be. Through the application of these means, certain laws or characteristics of traffic flow have been discovered or developed. This has made it possible to base this report on factual, technical data.

While compiling this report, the Highway Capacity Committee has reviewed all the available previously published information on the subject and has used the factual information obtained through investigations conducted by many individuals and organizations, especially the comprehensive traffic operation research investigations made by the Bureau of Public Roads in cooperation with the various State highway departments and other governmental agencies.

The Committee is especially indebted to the many city traffic engineers who contributed valuable data regarding intersection capacities, and to the Institute of Traffic Engineers for the help rendered in obtaining information on urban conditions.

The Committee is aware that highway capacities have been increasing over a period of years due to improved vehicle design, increased skill of drivers, and improved traffic control. With the introduction of four-wheel brakes, for example, closer spacing of vehicles was possible.

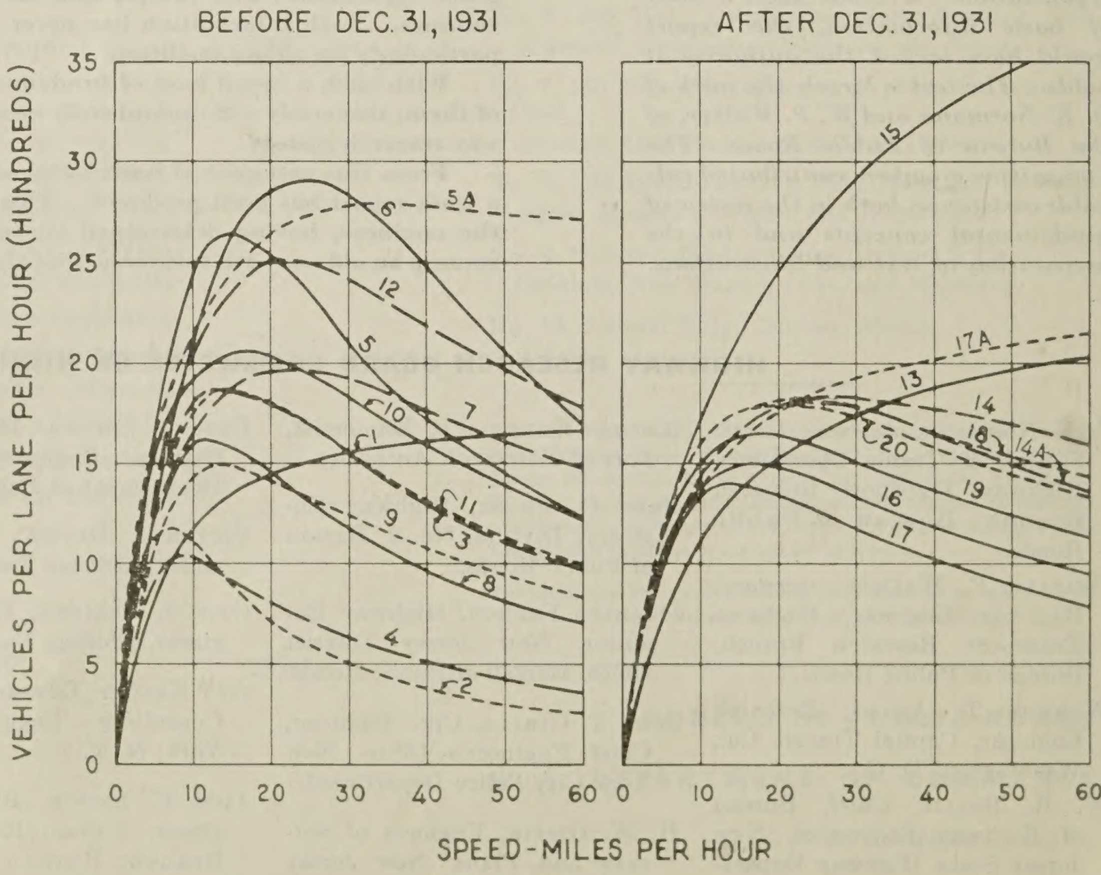
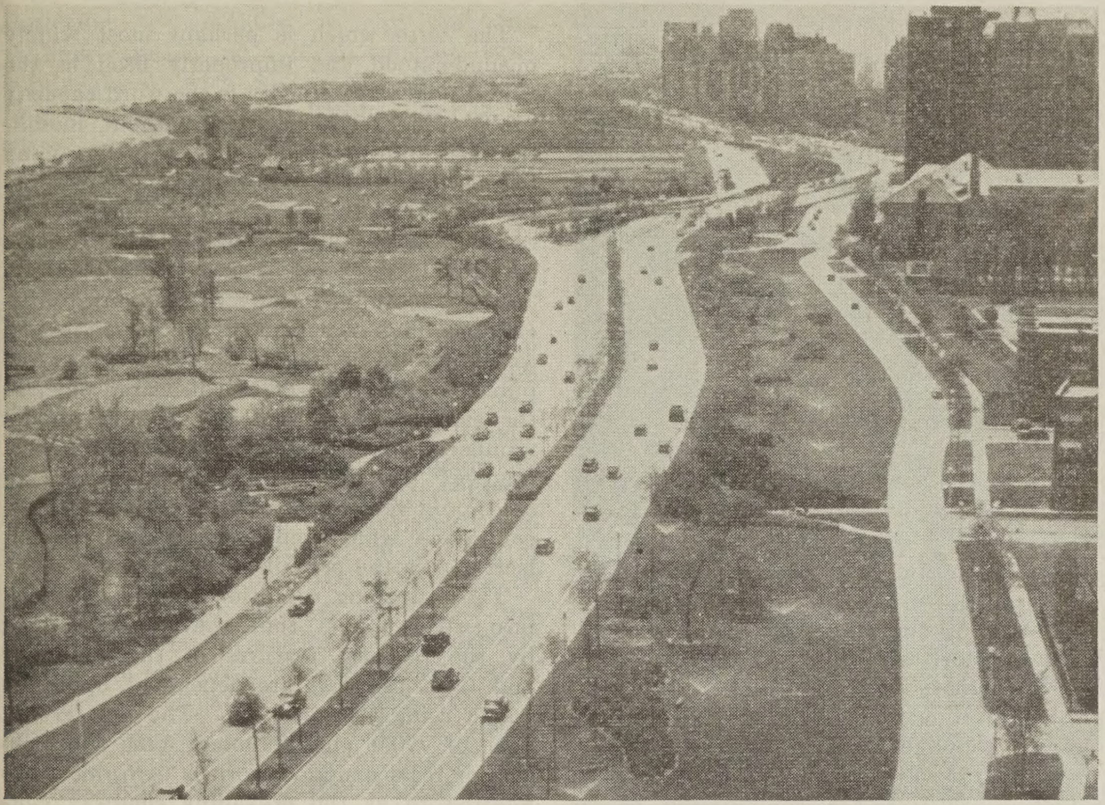


Figure 1.—Calculated capacities of a single traffic lane, from various sources.

Highway Capacity Stabilized

Improvements will continue to be made. The Committee believes, however, that capacities of highways are becoming stabilized insofar as the effects of the vehicle and the driver are concerned. Improvements which might tend to increase capacities will probably be offset, to some extent at least, by other factors. If the large number of rear-end collision accidents are to be appreciably reduced, for example, drivers must maintain somewhat longer distances between vehicles while operating in high traffic densities. A recent study of vehicle spacings under capacity conditions showed that 28 percent of the drivers could not have avoided a rear-end collision had the driver of the preceding vehicle suddenly applied his brakes. This assumes good brakes on both vehicles, and an extremely low value of 1 second for the combined perception and reaction time. The capacity figures in this report, therefore, are based on present-day vehicles and the manner in which they are currently operated on the various types of highway facilities.

By correctly applying the various factors affecting street and highway capacities shown in this report, the engineer can evaluate quantitatively the deficiencies of long stretches of highways between important termini or between important intersections several miles apart. This will help to eliminate the common failure to recognize the need for improvement until a facility becomes badly congested. Instead, the need for improvement can be anticipated and the projects placed in their proper position in a long-range priority program for a street or highway system. Also, it should no longer be necessary to continually "chase rainbows" by increasing the capacity at one point only to find that the traffic bottleneck has been transferred to some other point along the route, with comparatively little overall benefit to traffic.



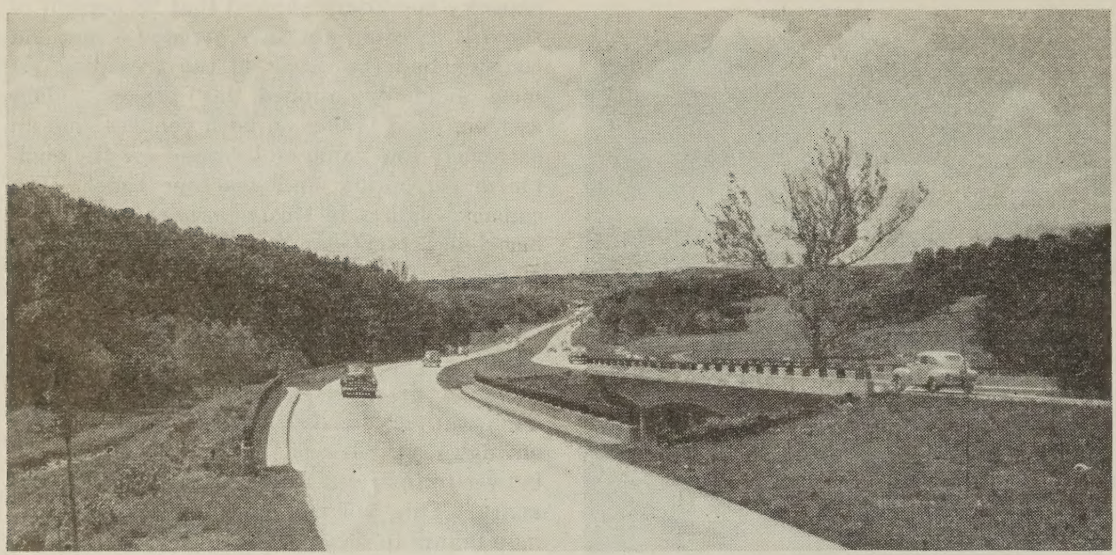
Lake Shore Drive in Chicago has an outstanding record for moving huge volumes of traffic.

Table 1.—*Calculated capacities of a single traffic lane, from various sources*

Formula No.	Author	Year of publication	Safe following distance S when V is the speed in miles per hour	Assumed distance between cars at standstill (center to center)	Assumed reaction time	For maximum capacity—		Maximum capacity
						Speed	Spacing	
			Feet	*Feet*	*Seconds*	*M.p.h.*	*Feet*	*V.p.h.*
1	Schwanter	1924	$2.933V+14.7$	14.7	2.00	∞	(2.0 sec.)	1,800
2	French periodical	1924	$0.337V^2+14.7$	14.7	0	6.6	29.4	1,190
3	Lewis	1925	$0.0742V^2+0.733V+14.7$	14.7	0.50	14.1	39.7	1,870
4	Schaar	1925	$0.213V^2+1.47V+14.7$	14.7	1.00	8.3	41.6	1,050
5	Johnson	1926	$0.0667V^2+15$	15	0	15.0	30.0	2,640
5A	do	1928	$0.5V^{2.3}+15$	15	0	34.3	64.6	2,800
6	Kelker	1926	(1)	17.6		25.0	45.5	2,900
7	Highway Research	1927	$0.0366V^2+1.10V+17$	17	0.75	21.5	57.7	1,970
8	Weninger	1929	$0.109V^2+0.733V+14.7$	14.7	0.50	11.6	37.9	1,610
9	Ehlgotz	1929	$0.0773V^2+1.47V+14.7$	14.7	1.00	14.2	50.3	1,490
10	Daugherty	1930	$0.0556V^2+0.733V+15$	15	0.50	16.4	42.1	2,060
11	New York Regional	1931	$0.072V^2+0.733V+15$	15	0.50	14.4	40.6	1,870
12	Allan	1931	$0.0333V^2+0.733V+14$	14	0.50	20.5	43.0	2,520
13	Johannesson	1933	$2.20V+25$	25	1.50	∞	(1.5 sec.)	2,400
14	Massachusetts WPA	1934	$0.025V^2+1.47V+20$	20	1.00	28.3	81.5	1,830
14A	do	1934	$0.0102V^{2.3}+1.47V+20$	20	1.00	24.1	70.7	1,800
15	Greenshields	1935	$1.10V+21$	21	0.75	∞	(0.75 sec.)	4,800
16	Birula	1935	$0.0635V^2+1.47V+16.4$	16.4	1.00	15.8	55.5	1,500
17	Nevins	1939	$0.0833V^2+1.47V+16$	16	1.00	13.9	52.4	1,400
17A	do	1939	$2.20V+16$	16	1.50	∞	(1.50 sec.)	2,400
18	Clayton	1941	$0.0333V^2+1.47V+15$	15	1.00	21.2	61.1	1,830
19	do	1941	$0.05V^2+1.47V+15$	15	1.00	17.3	55.4	1,650
20	Gulstad	1941	$0.0373V^2+1.47V+15$	14.7	1.00	19.8	58.4	1,790

[1] Kelker, who did not list a formula of his own, assumed that at 10 m. p. h. the time spacing between vehicles is 0.5 second and at 60 m. p. h. is 2.0 seconds. These two points were joined with a straight line on semi-log cross-section paper.

Part I—Definitions



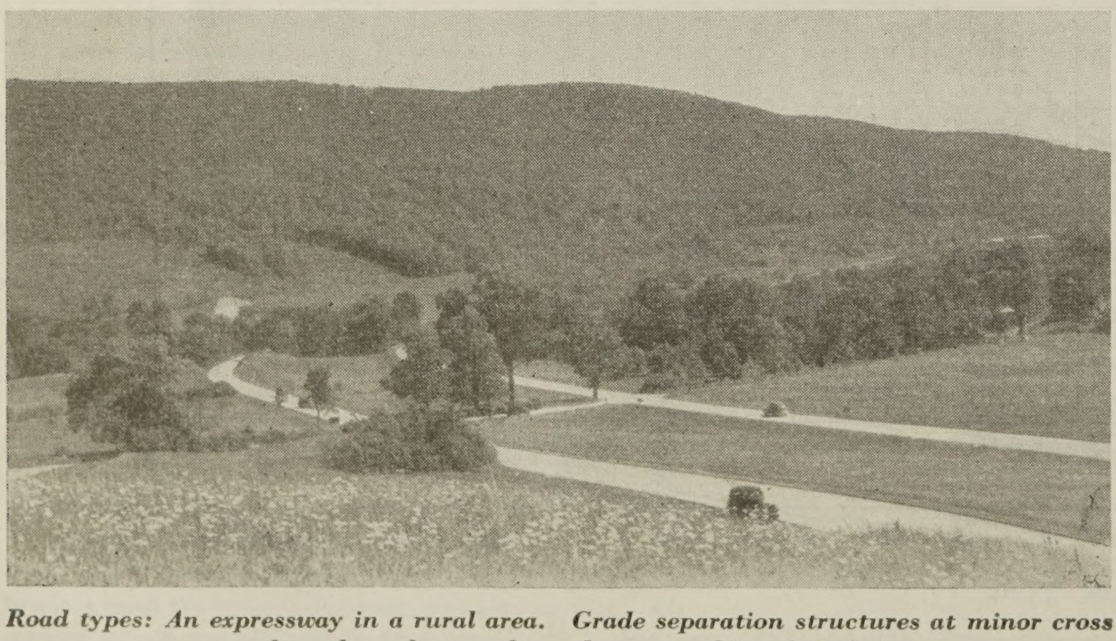
Road types: A freeway.

INTRODUCTION

The confusion that has existed concerning the meaning and shades of meaning of many terms used in traffic engineering practice has contributed, in some measure at least, to the wide differences of opinion regarding the capacity of various highway facilities. To cite but one of many examples, it is not uncommon to find the terms **high traffic density** and **high traffic volume** used synonymously or interchangeably. This practice is incorrect and creates misunderstanding in connection with highway capacities because **traffic volume** is a product of the traffic density and the traffic speed. As will be shown later, it is possible to have a very low traffic volume with a high traffic density. In fact, the highest traffic densities do occur when vehicles are practically at a standstill, in which case the traffic volume would approach zero.

The definitions given here are intended to be those most descriptive and most widely used in engineering practice. Most of them are based on current usage or are definitions already adopted by various organizations. There are, however, many cases in which a definition represents a combination of, or compromise between, definitions appearing in previously published material. The Committee's primary attempt has been to ascribe definite meanings to terms as they have been used in this report, thus minimizing likelihood of misinterpretation of its content.[1]

Included also are definitions for terms not used in this report, but the use of which will probably be necessary as the investigations of highway capacity are broadened to cover many of the specific conditions for which data are not now available.



Road types: An expressway in a rural area. Grade separation structures at minor cross roads such as the one shown here are seldom justified.

CAPACITY DEFINED

The term which is perhaps most widely misunderstood and improperly used in the field of highway capacity is the word **capacity** itself. The term **capacity,** without modification, is simply a generic expression pertaining to the ability of a roadway to accommodate traffic. Like the power of an engine, the capacity of a roadway must be rated by some standard before it can be expressed intelligibly. Just as the ability of any given pump to discharge a liquid is dependent upon such factors as the nature of the liquid, the speed of the pump, and the size of the discharge pipe, so the capacity of a roadway depends upon a number of conditions. Composition of traffic, roadway alinement, number and width of lanes, and vehicular speeds are a few of these conditions which may be referred to collectively as the **prevailing conditions.**

The prevailing conditions may be divided into two groups: (1) those that are determined by the physical features of the roadway; and (2) those that are dependent upon the traffic using the roadway. The first group, none of which change unless some construction or reconstruction work is performed, are referred to as the **prevailing roadway conditions.** The second group, any of which may change or be changed from hour to hour or during various periods of the day, are referred to as the **prevailing traffic conditions.**

Basic Capacity

There are three levels of roadway capacity that are of utmost importance in any discussion of the subject. The first of these the Committee has decided to call the **basic capacity. It is the maximum number of passenger cars that can pass a given point on a lane or roadway during one hour under the most nearly ideal roadway and traffic conditions which can possibly be attained.**

Basic capacity for rural roads and urban expressways with uninterrupted flow is expressed in terms of passenger cars per lane or roadway per hour. Basic capacity for street intersections applies to the roadway width on one approach and is the rate of flow expressed in terms of passenger cars per hour, during the period that the flow is not interrupted. Two roadways having the same physical features, therefore, have the same basic capacity regardless of the prevailing traffic conditions.

Possible Capacity

The second level of capacity is **the maximum number of vehicles that can pass a given point on a lane or roadway during one hour, under the prevailing roadway and traffic conditions.** This level of capacity, which the Committee has decided to call the **possible capacity,** is a positive quantity. **It is the volume of traffic that cannot be exceeded in**

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[1] The definitions do not necessarily agree with those of other committees or associations, and may be subject to change to foster national uniformity of nomenclature.

actuality without changing one or more of the conditions that prevail. It is necessary always to state the conditions under which an expressed possible capacity is applicable. For example, it would be incorrect to state that the possible capacity of a two-lane highway is 2,000 vehicles per hour. If, however, the statement be amplified to say that the possible capacity of a level, tangent, two-lane highway with a 24-foot surface, free from lateral obstructions within 6 feet of its edges, and with no major intersections at grade, is 2,000 passenger cars per hour, then it is substantially complete and correct.

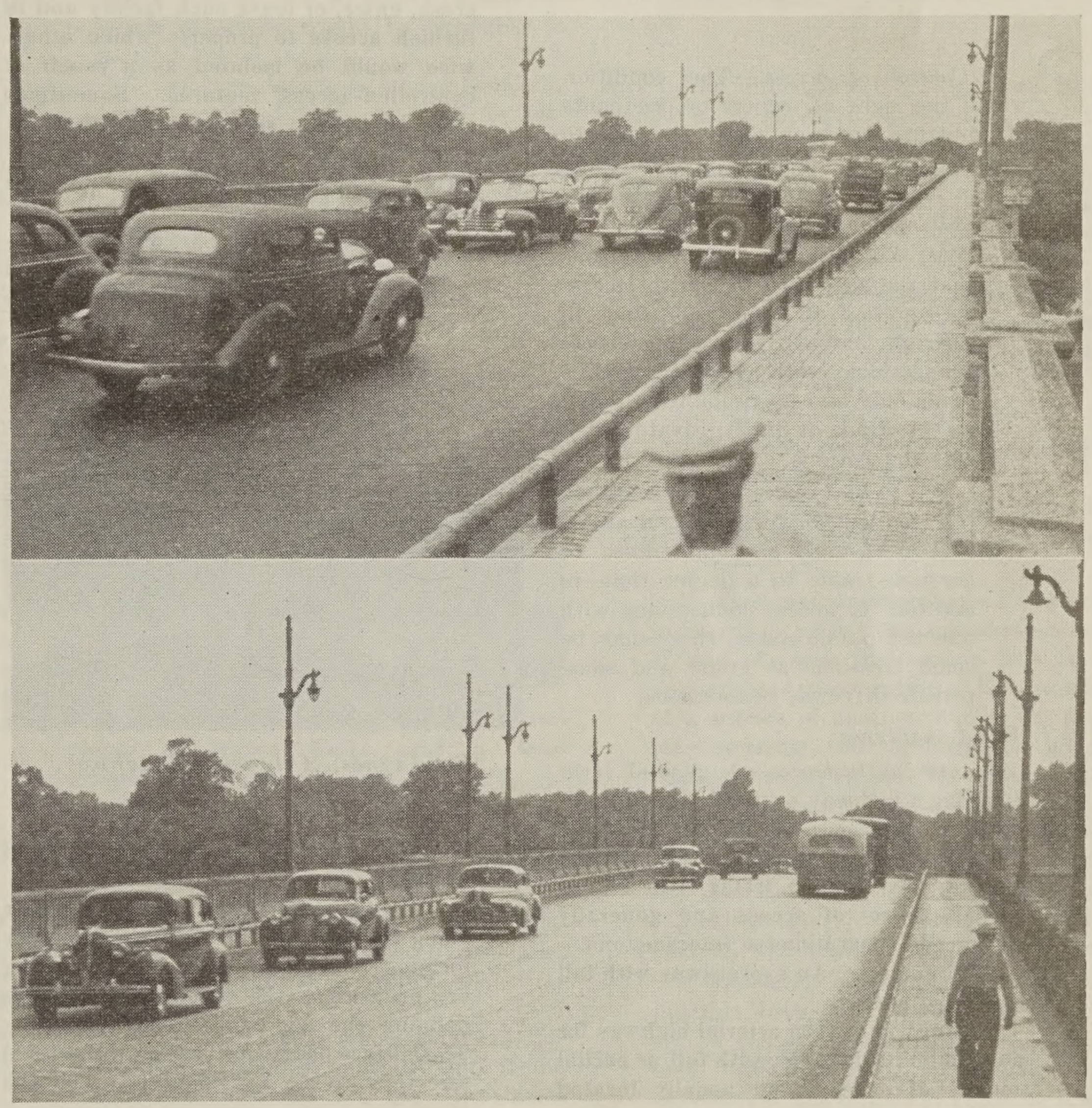
Practical Capacity

The third level of capacity is **the maximum number of vehicles that can pass a given point on a roadway or in a designated lane during one hour without the traffic density being so great as to cause unreasonable delay, hazard, or restriction to the drivers' freedom to maneuver under the prevailing roadway and traffic conditions.** This type of capacity the Committee has decided to call **practical capacity.** Because the phrase **unreasonable delay or restriction to the drivers' freedom to maneuver** is somewhat subjective, the establishment of the volume at which practical capacity is reached depends in large measure upon individual judgment. The reader will find, however, that the body of the report develops scientific means of rationalizing the extent to which the driver of a vehicle is deprived of his freedom to maneuver at various traffic volumes by considering the amount that his speed and other factors are restricted by other vehicles on the highway. By using this as a criterion, the Committee has found it possible to recommend definite ranges of practical capacities for various roadway and traffic conditions.

It is the practical capacity which is of primary interest to those striving to provide adequate highway facilities. The design engineer will plan his improvements with an adequate practical capacity to meet anticipated volumes of traffic on the facility. To him, a more descriptive term might be **design capacity,** but the only difference is that the highway has a design capacity during the planning stage, and a practical capacity after it is constructed. One is objective, the other reality, but both may have the same numerical value. It seems illogical, therefore, to introduce a second term having essentially the same meaning.

Other Terms

Other terms, such as **satisfactory capacity, tolerable capacity,** and **intolerable capacity** have been variously used in previously published material to subdivide the range between practical and possible capacities. For urban conditions where traffic is regulated by traffic signals, the report will show that the difference between practical and possible capacities is so small that intermediate levels are not needed. In rural areas, however, and on urban facilities having expressway characteristics, there is indeed a wide range in volume between practical capacity and possible capacity. This may be thought of as a reservoir which can absorb an overload, with increasing inconvenience to drivers, after the practical capacity has been reached. The report will show that within this realm congestion increases in direct ratio with the traffic volume. Because the conditions that govern the degree of congestion which may be considered as tolerable are so local in character, the Committee chooses to refrain from any specific recommendations for these intermediate terms. Considered more important is the need to inform the reader of the effect of these intermediate traffic volumes. Having been thus informed, the local official will be better able to exercise sound judgment in deciding upon satisfactory or tolerable capacities for use in administering his available funds to the greatest advantage of the public.



These two photographs, taken at the same location within a short period of time, illustrate the difference between traffic volume and traffic density. The volume in both cases was about the same. The density, because of slow speeds, was far greater in the upper picture than in the lower picture, where speeds were appreciably higher. Heavy congestion often creates the false impression, in a photograph, of high volume. Actually, pictures of free-flowing, high-volume roads usually show only a few vehicles in the field of vision.

The three forms of capacity, **basic, possible,** and **practical,** are the ones used throughout the report, and they are used in the sense just described. Other terms and their definitions follow, not in alphabetical order, but grouped according to the subject to which they are most closely related. As an aid in locating the definition of any term listed, an index will be found immediately following the glossary.

I.—ROADWAY DEFINITIONS

Highway, street, or road.—These are general terms denoting a public way for purposes of vehicular travel, including the entire area within the right-of-way. In rural areas, or in urban areas where there is comparatively little access and egress, a way between prominent termini is usually called a **highway** or a **road.** A way in an urban area with, or with provision made for curbs, sidewalks, and paved gutters, is ordinarily called a **street.**

Road types: A two-lane rural highway.

a. Control of access.—The condition where the right of owners or occupants of abutting land or other persons to access, light, air, or view in connection with a highway is fully or partially controlled by public authority.

(*1*) *Full control of access* means that the authority to control access is exercised to give preference to through traffic by providing access connections with selected public roads only and by prohibiting crossings at grade or direct private driveway connections.

(*2*) *Partial control of access* means that the authority to control access is exercised to give preference to through traffic to a degree that, in addition to access connections with selected public roads, there may be some crossings at grade and some private driveway connections.

1. *Functional types:*

a. Arterial highway.—A general term denoting a highway primarily for through traffic, usually on a continuous route.

b. *Expressway.*—A divided arterial highway for through traffic with full or partial control of access and generally with grade separations at intersections.

c. *Freeway.*—An expressway with full control of access.

d. *Parkway.*—An arterial highway for noncommercial traffic, with full or partial control of access, and usually located within a park or a ribbon of parklike development.

e. *Major street* or *major highway.*—An arterial highway with intersections at grade and direct access to abutting property, and on which geometric design and traffic control measures are used to expedite the safe movement of through traffic.

f. Through street or *through highway.*—Every highway or portion thereof at the entrance to which vehicular traffic from intersecting highways is required by law to stop before entering or crossing the same and when stop signs are erected.

g. Local street or *local road.*—A street or road primarily for access to residence, business, or other abutting property.

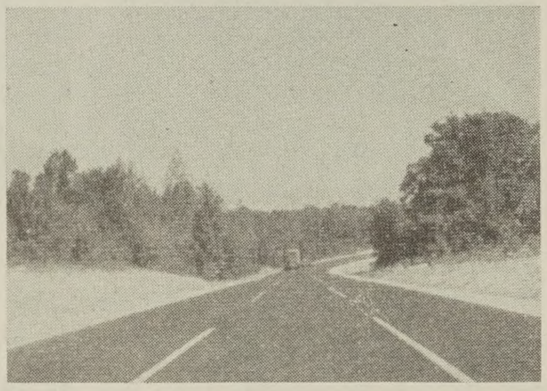
2. *Cross-section components:*

a. Roadway.—That portion of a road which is improved, designed, or ordinarily intended for vehicular use. Divided roads, and roads with frontage roads, have more than one roadway. On undivided roads without frontage roadways, the roadway width normally lies between the regularly established curb lines or between the outer extremities of the shoulders, whichever is appropriate.

b. *Frontage roadway.*—A roadway contiguous to and generally paralleling an expressway, freeway, parkway, or through street so designed as to intercept, collect, and distribute traffic desiring to cross, enter, or leave such facility and to furnish access to property which otherwise would be isolated as a result of controlled-access features. Sometimes referred to as a *service roadway.*

c. Pavement.—That part of a roadway having a constructed surface for the facilitation of vehicular movement.

d. Shoulder.—That portion of a roadway between the outer edge of the paved surface and the curb or the inside edge of the ditch or gutter or original ground surface.



Road types: A three-lane highway.

e. Curb.—A vertical or sloping member along the edge of a pavement or shoulder forming part of a gutter, strengthening or protecting the edge, and clearly defining the edge to vehicle operators. The surface of the curb facing the general direction of the pavement is called the "face."

(*1*) *Vertical curb.*—A curb whose face is a plane surface which is either vertical or inclined at an angle not exceeding 20 degrees with the vertical. Ordinarily it is not mountable, or is mountable with difficulty, by vehicles. Also called a *straight curb* or *normal curb.*

(*2*) *Sloped curb.*—A curb whose face is a plane surface which is inclined at an angle of at least 20 degrees, but not more than 60 degrees, with the vertical. It may be mountable or nonmountable by vehicles.

(*3*) *Lip curb.*—A curb whose face is a plane surface which is inclined at an angle of at least 60 degrees with the vertical and which is readily mountable by a vehicle.

(*4*) *Rolled curb.*—A curb, the face of which is S shaped in cross section, usually so constructed as to be mountable by a vehicle.

f. Separator.—An area or a device (other than a painted line or area) so located longitudinally between two roadways as to separate traffic flowing in the same or opposite directions and being so designed as to discourage or prevent passage by vehicles from the lanes on one side of the separator to those on the other.

(*1*) *Directional separator.*—A separator between traffic streams moving in opposite directions. If the directional separator is located between two roadways carrying through traffic in opposite directions, it is usually referred to as a ***Median.***

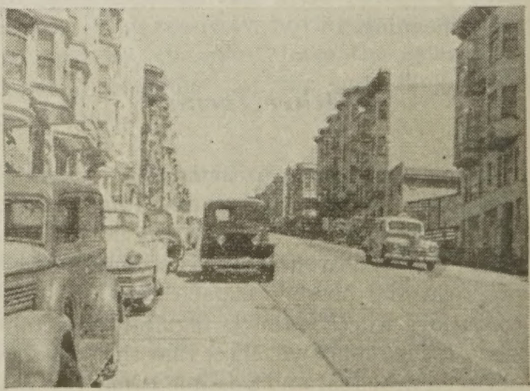
(*2*) *Lane separator.*—A separator between traffic streams moving in the same direction where the service rendered by the roadways on either side of the separator is essentially of the same character, as distinguished from that on a frontage roadway.

(*3*) *Outer separator.*—A separator between a frontage roadway and the roadway of a controlled-access highway or major street.

g. *Speed change area.*—An added width of pavement adjacent to the through traffic lanes to enable vehicles entering a roadway to accelerate to a reasonable speed before merging with through traffic or to permit vehicles leaving the roadway to decelerate to the required speed after separation from through traffic has been accomplished.

(*1*) *Acceleration area.*—A speed change area for the purpose of: (*a*) Enabling a vehicle entering a roadway to increase its speed to a rate at which it can more safely merge with through traffic; (*b*) Providing the necessary merging distance; and (*c*) Giving the main roadway traffic the necessary time and distance to make appropriate adjustments.

(*2*) *Deceleration area.*—A speed change area for the purpose of enabling a vehicle that is to make an



Road types: A one-way street.

exit turn from a roadway to slow to the safe speed on the curve ahead after it has left the main stream of faster-moving traffic.

3. *Cross-sectional design:*

a. Undivided road.—A road which has no directional separator, either natural or structural, separating traffic moving in opposite directions.

b. Divided road.—A two-way road on which traffic in one direction of travel is separated from that in the opposite direction by a directional separator. Such a road has two or more roadways.

4. *Width in lanes:*

a. Two-lane road.—An undivided two-way road having one lane for traffic in each of two opposing directions.

b. Three-lane road.—An undivided two-way road providing one lane for the exclusive use of traffic in each of two opposing directions and a third (center) lane for use by traffic in either direction in overtaking and passing.

c. Odd-lane road.—An undivided two-way road having an odd number of lanes, one of which may be used by traffic moving in either direction. A three-lane roadway is a specific type of odd-lane roadway.

d. Multilane road.—A road having two or more lanes for traffic in each direction, or four or more lanes for traffic in two directions. It may be one-way or two-way; divided or undivided.

5. *Directional usage:*

a. One-way road.—A road on which the movement of traffic is confined to one direction.

b. Two-way road.—A road on which traffic may move in opposing directions simultaneously. It may be either divided or undivided.

6. *Traffic lane.*—A strip of roadway intended to accommodate a single line of moving vehicles.

a. *Right lane* or *first lane*.—On any roadway, the lane on the extreme right, in the direction of traffic flow, available for moving traffic. Sometimes referred to as the outside lane on rural highways or the curb lane on city streets where parking is not permitted.

b. *Left lane*.—(*1*) On a two-lane, two-way road, that lane which is to the left of the center line and which is normally used by traffic in the opposite direction.

(2) On a multilane road, the extreme left-hand lane of those lanes available for traffic traveling in one direction.

Road types: A major street with left-turn lanes and separate signal indications for vehicles turning left.

c. *Center lane*.—On an undivided road having an odd number of lanes, the lane which may be used by traffic traveling in either direction.

d. *Second lane, third lane, etc.*—On a multilane road, lanes to the left of the right lane (or first lane), available for traffic traveling in the same direction are designated "second lane," "third lane," etc., in that order.

e. Parking lane.—A strip of roadway where vehicles may be legally parked but which otherwise would be available to moving traffic.

f. Left-turn lane.—A lane within the normal surfaced width, reserved for left-turning vehicles.

g. Right-turn lane.—A lane within the normal surfaced width, reserved for right-turning vehicles.

h. Separated turning lanes.—Added traffic lanes separated from the intersection area by an island or unpaved area. They may be wide enough for one-lane or two-lane operation.

Road types: An expressway having a directional separator (left) and a lane separator.

i. Added turning lane.—A special lane for turning vehicles obtained by widening the normal roadway width at intersections.

j. Turn-out lane.—A special lane of limited length apart from the through traffic lanes provided for the use of vehicles making stops of short duration.

k. Car-track lane.—A lane occupied by streetcar tracks within the surfaced width of a roadway. Such a lane may or may not be available for use by free-wheeled vehicles.

7. *Intersection.*—The area embraced within the prolongation or connection of the lateral curb lines, or, if none, then the lateral boundary lines of the roadways of two highways which join one another at, or approximately at, right angles, or the area within which vehicles traveling upon different highways joining at any other angle may come in conflict. Where a highway includes two roadways (30) feet or more apart, then every crossing of each roadway of such divided highway by an intersecting highway shall be regarded as a separate intersection. In the event such intersecting highway also includes two roadways (30) feet or more apart, then every crossing of two roadways of such highways shall be regarded as a separate intersection.

Road types: A major street with frontage roads. Lamp posts are mounted in the outer separators.

a. Intersection leg.—That part of any one of the roadways radiating from an intersection which is outside of the area of the intersection proper.

(*1*) *Approach.*—That portion of a leg which is used by traffic approaching the intersection.

(*2*) *Exit.*—That portion of a leg which is used by traffic in leaving an intersection.

b. Three-way intersection.—A roadway intersection with three intersection legs. If one of these intersection legs is an approximate prolongation of the direction of approach of another, and if the third leg intersects this prolongation at an angle between 75 and 105 degrees, the three-way intersection is classed as a T intersection. If one leg is a prolongation of the approach of another, and the third leg intersects this prolongation at an angle less than 75 or greater than 105 degrees, it is classed as a Y intersection.

c. Four-way intersection.—A roadway junction with four intersection legs. If two of the intersection legs are approximate prolongations of the directions of approach of the other two, and the angle of intersection of these two prolongations is less than 75 degrees or more than 105 degrees, it is classed as a four-way oblique intersection. If two of the intersection legs are approximate prolongations of the other two legs, and the angle of intersection of these prolongations is 75 degrees or more, but not greater than 105 degrees, it is classed as a four-way right-angled intersection.

d. Multiway intersection.—A junction having five or more legs.

e. Rotary intersection.—A confluence of three or more intersection legs at which traffic merges into and emerges from a one-way roadway in a counterclockwise direction around a central area.

(*1*) *Traffic circle.*—A rotary intersection having a central area circular or oval in shape of sufficient size to produce weaving maneuvers in lieu of direct crossings between the various movements.

8. *Highway grade separation.*—A structure used to separate vertically two intersecting roadways, thus permitting traffic on the one road to cross traffic on the other road without interference.

a. Traffic interchange or *interchange.*—A system of interconnecting roadways in conjunction with a grade separation or grade separations providing for the interchange of traffic between two or more roadways or highways on different levels.

b. Access ramp or *ramp.*—An interconnecting roadway of a traffic interchange, or any connection between highway facilities of different levels, on which vehicles may enter or leave a designated roadway.

(*1*) *Inner loop.*—A ramp used by traffic destined for a left-turn movement from one of the through roadways to a second when such movement is accomplished by making a right-exit turn followed by a three-quarter-round right-turn maneuver and a right-entrance turn.

(*2*) *Outer connection.*—A ramp used by traffic destined for a right-turn movement from one of the through roadways separated by a structure to the second through roadway.

(*3*) *Direct connection.*—A form of ramp which does not deviate much from the intended direction of travel. The inner loop for left-turning movement is avoided by the use of separate structures. An outer connection is a direct connection for right-turning movements.

Intersection types: A four-way intersection in a downtown area.

(*4*) *Exit turn.*—A turn at a ramp terminal where traffic leaves a through roadway and enters a ramp.

(*5*) *Entrance turn.*—A turn at a ramp terminal where traffic turns from a ramp and enters a through roadway.

9. *Weaving section.*—A length of one-way roadway serving as an elongated intersection of two one-way roads crossing each other at an acute angle in such a manner that the interference between cross traffic is minimized through substitution of weaving for direct crossing of vehicle pathways.

***10. Sight distance.*—The length of roadway visible to the driver of a passenger vehicle at any given point on the roadway when the view is unobstructed by traffic.**

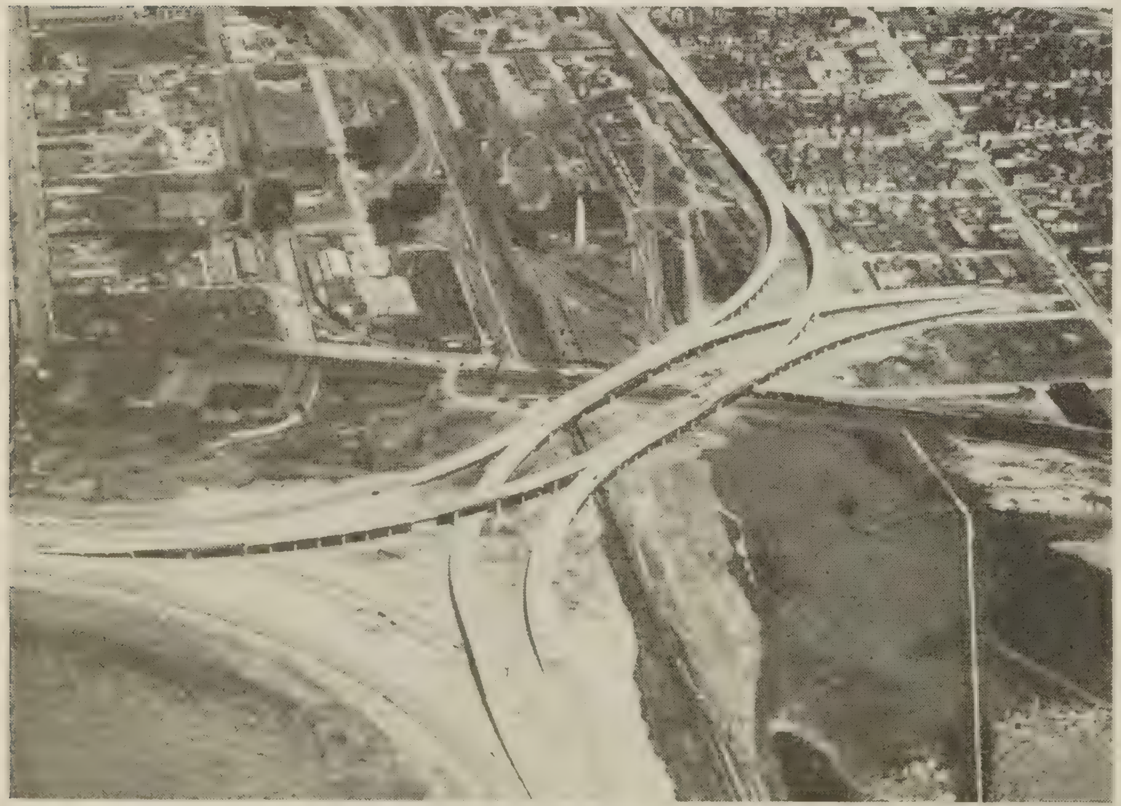
***a. Stopping sight distance.*—The distance required by a driver of a vehicle, traveling at a given speed, to bring his vehicle to a stop after an object on the roadway becomes visible.**

***b. Passing sight distance.*—The minimum sight distance that must be available to enable the driver of one vehicle to pass another vehicle safely and comfortably without interfering with the speed of an oncoming vehicle traveling at the design speed should it come into view after the overtaking maneuver is started.**

***c. Restricted stopping sight distance.*—A sight distance shorter than the stopping sight distance for the design speed.**

***d. Restricted passing sight distance.*—A sight distance shorter than the passing sight distance required to pass a vehicle traveling 10 miles per hour slower than the design speed.**

***e. Restrictive sight distance.*—A sight distance which, by reason of its inadequate length, causes a reduction in the operating speed and otherwise restrains the free movement of traffic under the prevailing conditions.**



Weaving sections: The distribution structure for the San Francisco-Oakland Bay Bridge (photo taken during construction in 1937).

II.—TRAFFIC CONTROL DEVICE DEFINITIONS

Traffic control devices.—A traffic control device is any sign, signal, marking, or device placed or erected for the purpose of regulating, warning, or guiding traffic.

1. *Pavement markings:*

a. Lane line.—A marked longitudinal line other than a center line separating two lanes.

b. Center line.—A marked center line (geometric medial line) of an undivided roadway.

c. Division line.—A line that designates the lanes available for traffic moving in each direction on an undivided roadway and that is to one side of the center line.

d. Barrier line.—A distinctive longitudinal pavement line which, when placed in proper relation to a center line, lane line, or division line, indicates that all traffic should keep to the right of such barrier line.

e. Insert.—A pavement marking accomplished by setting into or attaching to the pavement a material (other than paint) of contrasting color flush or practically flush with the surface.

f. Button.—A pavement marking consisting of an inflexible object attached to the pavement and projecting above the surface.

g. Word markings.—Word messages marked on the pavement to aid in the control of traffic.

h. Directional pavement markings.—Directional lines, arrows, or symbols marked on the pavement to aid in the control of traffic.

2. *Traffic sign.*—A device mounted on a fixed or portable support whereby official notice is given in the form of words or symbols,

for the purpose of regulating, warning, guiding, or informing traffic.

a. Stop sign.—A sign indicating that traffic shall stop before proceeding.

3. Traffic signal.—A signal, operated manually, electrically, or mechanically, by which traffic is alternately commanded to stop and permitted to proceed.

a. Interval.—The time during which the traffic indication of any particular traffic signal face does not change.

b. Cycle.—The total time required for one complete sequence of the intervals of a traffic signal.

c. Phase.—A part of the total time cycle allocated to any traffic movement receiving the right-of-way or to any combination of traffic movements receiving the right-of-way simultaneously during one or more intervals.

d. Through band.—The time in seconds elapsing between the passing of the first and the last possible vehicle in a group of vehicles moving in accordance with the designed speed of a progressive signal system.

e. Manual control.—Operation of a traffic signal by hand.

f. Automatic control.—Operation of a traffic signal by an electrical timing mechanism.

g. Traffic-actuated control.—A type of automatic control which is actuated, under specific conditions, by impulses from individual vehicles or pedestrians, or both.

h. Independent control.—Operation of a traffic signal installation not in coordination with any other signal.

i. Coordinated control.—Operation of two or more traffic control signal installations with definite interrelation.

j. Simultaneous system.—A signal system in which all signals always give the same indication to a given street at the same time.

k. Alternate system.—A signal system in which alternate signals, or groups of signals, give opposite indications to a given street at the same time.

l. Progressive system.—A signal system in which the various signal faces controlling a given street give GO indications in accordance with a timing schedule to permit (as nearly as possible) continuous operation of groups of vehicles along the street at a planned rate of speed, which may vary in different parts of the system.

m. Flexible progressive system.—A signal system in which the intervals at any signal may be independently adjusted to the traffic requirements at the intersection, and in which the GO indications at separate signals may be started independently at the instant which will result in maximum efficiency.

4. Safety zones and islands:

a. Safety zone.—An area or space set apart within a roadway for the exclusive use of pedestrians and which is protected or is so marked or indicated by adequate signs as to be plainly visible at all times. When the area so set apart is for the protection of streetcar or bus passengers, it is known as a *loading zone*.

b. Pedestrian island.—A raised safety zone located in a cross walk.

c. Loading island.—A raised safety zone especially provided at a regular streetcar stop, or at a bus stop when such is near the middle of the street, for the protection of passengers.

d. Traffic island.—Any restricted area permanently located in a roadway which provides structurally for the physical separation and sorting of traffic streams.

e. Channelizing island.—A traffic island located in a roadway area to confine specific movements of traffic to definite channels.

f. Divisional island.—A traffic island so located longitudinally in a roadway as to separate traffic streams flowing in the same or opposite directions. (*See also* "Separator").

g. Rotary island.—A traffic island located in the center of an intersection to compel movement in a counterclockwise direction and thus substitute weaving of traffic around the island instead of direct crossings of vehicle pathways.

Road Types: A depressed expressway.

Intersection types: A multiway intersection.

III.—TRAFFIC AND TRAFFIC OPERATIONS DEFINITIONS

A.—Composition of Traffic

1. Traffic.—All types of conveyances, together with their load, either singly or as a whole, while using any roadway for the purpose of transportation or travel.

a. Vehicle.—Any component of traffic. Unless otherwise qualified, the term vehicle will normally apply to free-wheeled vehicles as hereinafter defined.

b. Free-wheeled vehicle.—Any component of traffic not limited in its field of operation to rails or tracks.

c. Passenger car.—A free-wheeled, self-propelled vehicle designed for the transportation of persons but limited in seating capacity to not more than seven passengers. It includes taxicabs, limousines, and station wagons, but does not include motorcycles.

d. Commercial vehicle.—A free-wheeled vehicle designed for the transportation of cargo other than passengers, and broadly referred to as a "truck." May be further classified as light-powered, medium-powered, and heavy-powered, and includes tractor-trucks, trailers, and semi-trailers when used in combination.

e. Motorbus (bus).—A free-wheeled vehicle having a self-contained source of motive power (as distinguished from a trolley coach), designed for the transportation of persons, and having a seating capacity of eight or more passengers.

f. Trolley coach or *trackless trolley.*—A vehicle, designed for the transportation of

Intersection types: A rural traffic circle.

Intersection types: An urban traffic circle.

passengers, which is propelled by electric power obtained from overhead trolley wires, but not operated upon rails.

g. Streetcar.—A single self-propelled vehicle restricted to operating on rails or tracks and designed for transporting passengers, principally within a municipality or contiguous area.

B.—Traffic Operation

1. *Speed.*—The rate of movement of traffic or of specified components of traffic, expressed in miles per hour.

a. *Average speed.*—The average of the speeds of all vehicles at a specified point on a given roadway, during a specified period of time.

b. *Over-all speed.*—The total distance traversed, divided by the total time required, including all traffic delays, expressed in miles per hour.

c. *Average over-all speed.*—The average of the over-all speeds of all vehicles on a given roadway during a specified period of time.

d. *Optimum speed.*—The average speed at which traffic must move when the volume is at a maximum on a given roadway. An average speed either appreciably higher or lower than the optimum will result in a reduction in volume. Also known as *critical speed.*

Left-turn lanes: Jackson Boulevard at Lake Shore Drive, Chicago. Provision of three left-turn lanes eastbound, one right-turn lane eastbound, and two lanes westbound, reduces to a minimum the requisite time allotted to turning movements, thus affording greater time for through traffic on Lake Shore Drive.

e. *Design speed.*—A speed selected for purposes of design and correlation of those features of a highway, such as curvature, superelevation, and sight distance, upon which the safe operation of vehicles is dependent. It is the highest continuous speed at which individual vehicles can travel with safety upon a highway when weather conditions are favorable, traffic density is low, and the design features of the highway are the governing conditions for safety.

f. *Operating speed.*—The highest over-all speed exclusive of stops at which a driver *can* travel on a given highway under prevailing conditions without at any time exceeding the design speed.

g. *Speed difference.*—The difference in the speeds of two successive vehicles moving in the same direction.

h. *Average speed difference.*—The average of the speed differences for all components of traffic on a given roadway during a specified period of time.

2. *Delay.*—The time consumed while traffic or a specified component of traffic is impeded in its movement by some element over which it has no control. Usually expressed in seconds per vehicle.

a. Fixed delay.—The delay to which vehicles are subjected during light traffic volumes or low densities. The delays experienced by a lone vehicle as a result of traffic signals or stop signs are fixed delays.

b. *Operational delay.*—The delay caused by the interference between components of traffic. The difference between travel times over a route during extremely low and high traffic volumes, and the time consumed while waiting at a stop sign for cross traffic to clear, are operational delays. Time losses resulting from congestion, from interference with parking vehicles, and from turning vehicles are also examples of operational delays.

3. *Headway.*—The interval of time between individual vehicles moving in the same lane measured from head to head as they pass a given point.

a. Average headway.—The average of the headways for vehicles on a given roadway during a specified period of time.

b. Minimum headway.—The existing headway when successive vehicles are moving as closely together as practical under prevailing conditions.

4. *Stopping distance:*

a. *Vehicle stopping distance.*—The distance traveled between the point at which the driver contacts the braking controls and the point at which the vehicle comes to rest.

b. *Braking distance.*—The total distance traversed by a vehicle while it is being brought to rest, measured from the position of the vehicle at the instant the brake shoe touches the brake drum.

c. *Driver stopping distance.*—The total distance traversed by a vehicle while it is being brought to rest, measured from the position of the vehicle at the instant the driver has an opportunity to perceive that he should stop his vehicle as quickly as possible. Includes the distance traveled during driver perception and reaction time.

5. Weaving.—The act performed by a vehicle in moving obliquely from one lane to another, thus crossing the path of other vehicles moving in the same direction.

6. Merging.—The process by which drivers in two separate traffic streams moving in the same general direction combine or unite to form a single stream.

7. *Volume.*—The number of vehicles moving in a specified direction or directions on a given lane or roadway that pass a given point during a specified period of time, viz., hourly, daily, yearly, etc.

a. *Average annual daily volume.*—The total yearly volume divided by the number of days in the year; commonly abbreviated as ADT.

b. *Maximum annual hourly volume.*—The highest hourly volume that

Road types: A turn-out lane on a freeway (New Jersey Route 100). The telephone booth is well patronized.

occurs on a given roadway in a designated year.

c. *Tenth highest annual hourly volume.*—The hourly volume on a given roadway that is exceeded by only nine hourly volumes during a designated year.

d. *Twentieth, thirtieth, etc., highest annual hourly volume.*—The hourly volume on a given roadway that is exceeded by 19, 29, etc., hourly volumes during a designated year.

8. *Density.*—The number of vehicles occupying a unit length of the moving lanes of a roadway at a given instant. Usually expressed in vehicles per mile.

a. *Average density.*—The average number of vehicles per unit length of roadway over a specified period of time.

b. *Critical density.*—The density of traffic when the volume is at the possible capacity on a given roadway. At a density either greater or less than the critical density the volume of traffic will be decreased. Critical density occurs when all vehicles are moving at or about the optimum speed.

9. *Variation in flow.*—The fluctuation in traffic volume on a given street or highway with successive periods of the day, month, season, or year.

10. *Traffic pattern.*—A tabular or graphical representation of the fluctuation in traffic volume over a specified period of time. The volume during the increments of time used in the pattern may be expressed as numbers of vehicles or as the percentage which these numbers are of the average number for all the increments covered by the pattern. Different facilities may be said to have like traffic patterns if identical curves result when traffic volumes are shown as a percentage of the average volume for the period covered by the pattern.

a. *Daily traffic pattern.*—A traffic pattern wherein traffic volumes for each of 24 consecutive hours are shown. If the period of time is extended to include 168 consecutive hours it is termed a *daily traffic pattern for 1 week.* In like manner, daily traffic patterns for 1 month, 1 year, or any other period of time may be obtained.

Road types: Intersection on an expressway at grade having an added turning lane for left-turning vehicles. Separated turning lanes for right-turning vehicles are visible at the left of the picture.

Road types: Turn-out lanes on an expressway. These lanes might also be classed as a frontage road.

b. *Weekly traffic pattern.*—A traffic pattern wherein daily traffic volumes for each of 7 consecutive days are shown. If the period of time is extended to include 30 consecutive days the pattern is termed a *weekly traffic pattern for 1 month,* and if volumes for 365 consecutive days are shown it is termed a *weekly traffic pattern for 1 year.*

c. *Seasonal traffic pattern.*—A traffic pattern wherein the average daily traffic volumes for each of several consecutive months or seasons, as may be specified, are shown.

d. *Yearly traffic pattern.*—A tabular or graphical array of all the hourly traffic volumes in 1 year arranged in descending order of their magnitude, either as numerical values or as percentages of the traffic on the average day.

IV.—LAND USAGE AND DEVELOPMENT DEFINITIONS

1. *Development:*

a. *Business development.*—Land occupied predominantly by establishments used in the transaction of business.

b. *Residential development.* — Property which is in the main improved with residences.

c. *Park development.*—Land which is dedicated, maintained, and used for recreational purposes.

d. *Agricultural development.*—Cultivated land used for producing agricultural products.

2. *Area or locality:*

a. *Urban area.*—The area included within and adjacent to a municipality or other urban place of 5,000 or more in population.

b. *Downtown area.*—That portion of a municipality in and surrounding a business development where ordinarily there are large numbers of pedestrians and a heavy demand for parking space during periods of peak traffic or a sustained high pedestrian volume and a continuously heavy demand for parking space during business and industrial employment hours. This definition applies to industrial and business areas outside of, as well as those within, the central part of a municipality.

c. *Intermediate area.*—That portion of a municipality which is outside of a downtown area but generally within the zone of influence of a business development, characterized by moderately heavy pedestrian traffic and a somewhat lower parking turn-over than is found in a downtown area.

d. *Outlying area.*—A residential development, or a mixture of residential and commercial establishments, within the outer fringe of a metropolitan area, characterized by few pedestrians and a low parking demand or turn-over.

e. *Rural area.*—Any area not within a town, city, or metropolitan area.

Road types: An elevated multilane highway.

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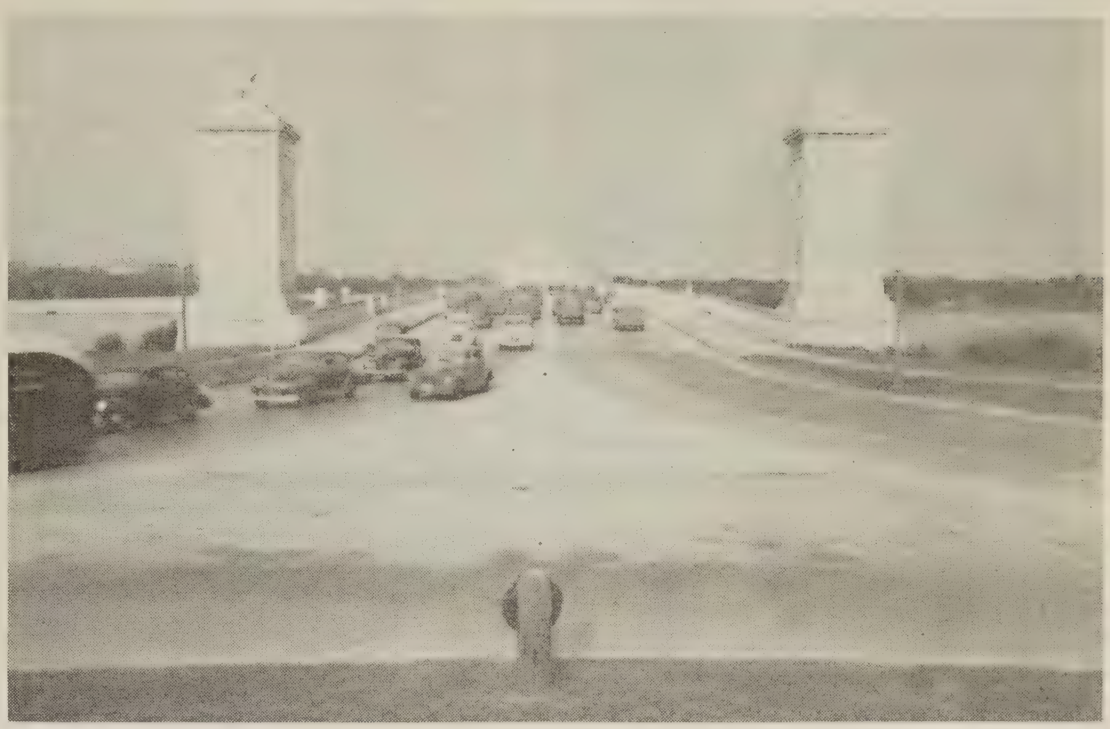
Part II.—Maximum Observed Traffic Volumes

Introduction

One method for determining the load-carrying ability of a machine or material is to apply stresses in successive increments of known quantity until the item being investigated is no longer able to support the burden imposed on it. In the industrial laboratory the strength, or capacity, of a test sample is usually determined by loading it to destruction, the greatest load it will support being its capacity. The highway engineer has at his disposal a comparable means for measuring the ability of a roadway to accommodate traffic. His laboratory extends throughout the country and his test samples are the many sections of highway that are repeatedly exposed to the maximum load they can possibly bear. His tools are a simple traffic counter and a timepiece. Because this is perhaps the earliest applied of all methods for studying highway capacity, it is fitting that some of the results obtained by this means be introduced early in a discussion of the subject.



Arlington Memorial Bridge, Washington, D. C. Low-speed approaches, lanes less than 12 feet wide, and high curbs limit the possible capacity of this roadway to about 4,000 vehicles per hour in one direction.

The analogy between the laboratory and the highway fails in one very important respect: In the laboratory the conditions under which the test is made can be carefully controlled, whereas the traffic engineer cannot readily alter either the roadway or traffic conditions that are prevalent during his test. He must note these conditions and make compensatory adjustments for the deviations from "standard" if his results are to be of any value. Because of failure to do this or to make similar adjustments in later applications of the data, the results obtained by this method have met with varying degrees of success.

Table 2.—*Maximum observed hourly volumes on two-lane roads*

Route and location	Average lane width	Vehicles per lane per hour	
		In one lane	Average for all lanes
	Feet		
Colorado St. Bridge, Pasadena, Calif	14.0	1,710	1,215
Sumner Tunnel, Boston, Mass	10.8	----------	1,200
Posey Tube, Alameda, Calif	11.5	1,400	1,350
U S 3, Manchester, N. H	10.0	----------	944
U S 45, Libertyville, Ill. (31 m.p.h.)	9.0	1,510	904
Lincoln Tunnel (1940), New York	10.8	1,152	----------
U S 1, Old Lyme, Conn	11.5	1,135	887
U S 27, north of Jct. Route 21, Mich	10.0	----------	850
U S 6, West Hartford, Conn	10.0	----------	830
State Route 17, northwest of Goshen, N. Y	10.0	----------	801
Shirley Highway (October 1944), at Glebe Road, Va. (27 m.p.h.)	12.0	1,251	752
Baltimore-Washington Blvd., Maryland	10.0	----------	751
State Route 9, Middletown, Conn	10.0	1,127	714
L & N Bridge, Cincinnati, Ohio	7.0	988	575
U S 285, near State Route 75, Denver, Colo	9.0	836	----------
State Route 87, Fayetteville, N. C	11.0	750	----------

Table 3.—*Maximum observed hourly volumes on three-lane roads*

Route and location	Average lane width	Vehicles per hour	
		In one direction	Average for all lanes
	Feet		
State Route 35, Laurence Harbor, N. J	10.0	2,250	1,021
State Route 27, Rahway, N. J	10.0	1,905	761
State Route 27, West Scott Ave., Rahway, N. J	10.0	1,814	724
U S 1, Danvers, Mass	10.0	1,526	664
State Route 29, Union County, N. J	10.0	1,511	757
State Route 42, Camden County, N. J	10.0	1,391	664
U S 40, Richmond, Calif	10.0	----------	653
State Route 17, Carlstadt, N. J	10.0	1,197	633
U S 101, Oceanside, Calif	10.0	----------	632
State Route 3, Quincy, Mass	10.0	920	568

Two- and Three-Lane Roads

Tables 2, 3, and 4 show the maximum hourly volumes that have been observed on a number of important highway facilities when the traffic flow was continuous. In each table the maximum traffic volume for one lane and for the average lane is shown. Values under the heading "In one lane" represent the maximum hourly volumes recorded for a single lane, except that for three-lane roads they represent the maximum hourly volumes for one direction of travel. The "Average for all lanes" is for both directions of travel on a two- or three-lane roadway and for all lanes in one direction of travel on a multilane roadway. The highest observed volume for one lane may or may not have occurred at the same time as the highest observed volume for the average lane.

The highest volume recorded for a two-lane roadway is 1,350 vehicles per lane in the Posey Tube at Alameda, Calif. A maximum volume of 1,710 vehicles in one lane has been observed on the Colorado Street Bridge in Pasadena, Calif. The roadway width of the latter is 28 feet and therefore might have been used, to some extent at least, as three lanes. Several other two-lane roadways have accommodated volumes exceeding 1,000 vehicles per hour in one direction but, as far as is known, these two facilities and the Sumner Tunnel are the only two-lane facilities that have accommodated an average of more than 1,000 vehicles per hour per lane or a total volume exceeding 2,000 vehicles per hour.

Lake Shore Drive, Chicago, operating with six lanes in the direction of heavier traffic movement. Separators between pairs of lanes can be raised or lowered at will, thus affording great flexibility in meeting traffic needs during various periods of the day.

Particular attention is called to the volume for the Baltimore-Washington Boulevard as shown in table 2. Several articles on highway capacity incorrectly report that 1,502 vehicles per lane were observed in 1 hour on this facility when it was a two-lane road. Examination of the original material reveals, however, that this figure was the total for both lanes and not for each lane. Similarly, many articles show the capacity of the Holland Tunnel as 2,000 vehicles per lane per hour. Actually, the Holland Tunnel has never carried more than a total of 2,505 vehicles in two lanes, or an average of 1,253 vehicles per lane per hour, as shown in table 4. Since each tube of the Holland Tunnel is a two-lane, one-directional facility, it is classed as a four-lane road.

A special attempt was made to obtain counts showing high hourly volumes on three-lane roads. Only one example was found, however, of a three-lane road with a peak hourly volume exceeding 3,000 vehicles, or 1,000 vehicles per lane per hour. On many three-lane facilities, average annual volumes in excess of 12,000 vehicles per day have been recorded. In one case the annual average 24-hour volume was 19,040 vehicles per day. Even with these high daily volumes, however, the maximum hourly volumes shown in table 3 have not been exceeded.

Multilane Facilities

Only two multilane facilities, U S 1 near the airport at Newark, N. J., and Grand Central Parkway, New York City, both with four-lane divided roads, have been reported as accommodating in excess of 2,000 vehicles per lane per hour (table 4).

The Outer Drive in Chicago is one of the best illustrations of high lane capacities on a road with a total of more than four lanes. It carries in the neighborhood of 1,500 vehicles per lane per hour nearly every day during the afternoon rush period. Maximums of 1,958 vehicles per lane when operating with four lanes in each direction and 1,640 vehicles per lane when operating with six lanes in one direction have been recorded.

Maximums Cited Are Exceptional

The volumes shown in tables 2, 3, and 4 are, in most cases, the possible capacities of those particular facilities. They are maximums that have been recorded only once, although the traffic demand has probably been sufficient to reach or exceed these same volumes on many occasions. Compared with a laboratory test of a number of identical samples of steel, these traffic counts correspond to the one test sample that would yield under a heavier load than all the others. Traffic on Memorial Bridge in Washington, D. C., for example, has been counted innumerable times when the bridge was unable to accommodate the approaching volume of traffic, thus causing traffic to back up on the approaches as a result of congestion on or near the bridge. During hundreds of such observations this bridge carried no more than 3,600 vehicles per hour in one direction, or an average of 1,200 vehicles per lane. On one occasion, however, and only on one occasion as far as is known, this bridge carried a total of 4,227 vehicles in one direction, or an average of 1,409 vehicles per lane.

Furthermore, the data included in tables 2, 3, and 4 were selected as the highest group of hourly volumes from a much larger list showing maximum observed volumes for facilities that, in the judgment of the observer, were loaded to their capacity. It would therefore be technically unsound to assume that other facilities with a comparable number of lanes would have the same capacities as the highest or even the average of these few isolated examples.

The maximum observed volumes are shown primarily to acquaint the reader with the peak traffic that has been carried on some of the more heavily traveled routes throughout the country. They are also intended to illustrate the wide range in capacities of facilities seemingly alike in type but actually having wide differences in their physical as well as traffic characteristics. The reasons for these wide differences in capacity will become more apparent as the subject is developed in succeeding chapters.

Table 4.—*Maximum observed hourly volumes in one direction on multilane roads*

Route and location	Average lane width (feet)	Vehicles per lane per hour	
		In one lane	Average for all lanes
FOUR-LANE ROADS			
U S 1, Newark Airport, N. J	12.4	----------	2,275
Grand Central Parkway, west of Parsons Blvd., N. Y	11.0	2,275	2,194
U S 73 and 75, Omaha, Nebr. (34 m.p.h.)	11.0	----------	1,763
Cross Bay Blvd., Queens, N. Y	8.0	----------	1,566
Express Highway, St. Louis, Mo	----------	1,956	1,543
Fourteenth St. Bridge, Washington, D. C. (27 m.p.h.)	10.0	1,620	1,508
Queensboro Bridge, upper roadway, New York, N. Y	11.25	1,861	1,488
Sunrise Highway, at Cross Bay Blvd., N. Y	10.0	----------	1,350
Outer Drive, Chicago, Ill	11.25	1,395	1,349
Southern State Parkway, Troopers Lodge, N. Y	10.0	----------	1,264
Holland Tunnel, New York, N. Y. (28 m.p.h.)	10.0	1,404	1,253
Edison Bridge, South Amboy, N. J	10.7	----------	1,246
Manhattan Bridge, New York, N. Y.:			
Upper roadway	11.25	1,884	1,226
Lower roadway	8.75	----------	912
Merritt Parkway, Greenwich, Conn	13.0	----------	1,158
Northern State Parkway, Troopers Lodge, N. Y	10.0	----------	1,136
Broadway Bridge, Portland, Oreg	10.0	----------	1,088
Williamsburg Bridge, New York, N. Y	10.0	----------	1,061
U S 20, Oxford, Mass	10.0	----------	1,042
FIVE-LANE ROADS			
Superior Bridge, Cleveland, Ohio	10.0	----------	1,557
Queensboro Bridge, New York, N. Y.:			
Lower roadway, two lanes one-way	10.2	1,720	1,292
Lower roadway, three lanes one-way	10.2	----------	1,195
SIX-LANE ROADS			
Henry Hudson Parkway, New York, N. Y	11.0	----------	1,666
Oakland Bay Bridge, San Francisco, Calif	9.7	----------	1,538
Leif Eriksen Drive, Chicago, Ill	11.6	----------	1,435
Memorial Bridge (30 m.p.h.) Washington, D. C	10.0	----------	1,409
Arroyo Seco Parkway, Los Angeles, Calif	10.7	----------	1,367
George Washington Bridge, New York, N. Y	8.0	----------	1,320
Delaware River Bridge, Camden, N. J. (four lanes one-way)	9.4	----------	1,285
Superior Bridge (12.5 m.p.h.), Cleveland, Ohio	10.0	1,530	1,241
Michigan Ave., Chicago, Ill	12.5	----------	1,118
Carnegie Ave., Cleveland, Ohio	9.5	1,098	938
Aurora Bridge, Seattle, Wash	9.3	1,111	903
Burnside Bridge, Portland, Oreg	10.0	----------	768
U S 1, Saugus, Mass	11.3	----------	746
Davison Expressway, Detroit, Mich	11.0	1,013	678
EIGHT-LANE ROADS			
Outer Drive (37 m.p.h.), Chicago, Ill	12.1	2,155	1,958
Curb lane (32 m.p.h.)	12.1	----------	1,519
Second lane (35 m.p.h.)	12.3	----------	2,155
Third lane (40 m.p.h.)	12.5	[1] 2,174	2,081
Fourth lane (40 m.p.h.)	11.7	----------	2,077
Six lanes one-way	11.25	----------	1,640
Figueroa Freeway, Los Angeles, Calif	10.0	----------	1,463

[1] The maximum in this lane occurred when the average lane carried only 1,681 vehicles per hour.

Part III.—Fundamentals of Highway Capacity

Introduction

The subject of street and highway capacity is not readily understood without a knowledge of the various factors which, either singly or in combination, affect the movement of vehicles. Principles of physics, dynamics, hydraulics, and the laws of various sciences have been applied from time to time to the movement of traffic with varying degrees of success. Although some of these laws are pertinent to traffic flow, a thorough knowledge of traffic movement has required the development of new principles.

Few drivers, if any, operate their vehicles in identically the same manner or react exactly the same under similar conditions. It is impossible, therefore, to predict the effect of various roadway and traffic conditions on an individual driver. It has been found, however, that the combined effect on traffic as a whole can be predicted with reasonable accuracy. This chapter is devoted to a few of the principles of traffic flow which relate to highway capacity.

Vehicle Spacings at Various Speeds

All drivers do not maintain the same distance spacing to the vehicle ahead when trailing at a given speed. In fact, the same driver in congested traffic will follow at different distances depending on the surroundings and his ability to match the speed of the preceding vehicle. Figure 2 shows the minimum distance spacings allowed by the average driver at different speeds for a few conditions. Similar curves based on thousands of observations for other conditions could be presented. The curves in figure 2 are, however, sufficient to show that the average driver increases the distance spacing between vehicles as his speed increases and that the spacing is also influenced by the characteristics of the highway.

Relation Between Speed and Basic Roadway Capacity

Using the data shown in figure 2, it is possible to determine the maximum number of passenger cars, one behind the other, that can pass a point in 1 hour at any given speed if this given speed is maintained by all vehicles. This is shown by figure 3. These curves have numerous practical applications if used correctly. **Under actual operating conditions it is possible to attain the traffic volumes shown for two-lane roads in one of the two lanes, but only upon the condition that there is no oncoming traffic in the other of the two lanes. Where traffic is moving in both directions on a two-lane road the combined volume in the two lanes may equal the values shown in figure 3. In fact, the total traffic volume over a section of two-lane, two-way road more than a few hundred feet long cannot exceed 2,000 vehicles per hour regardless of the distribution of traffic by directions. Likewise, the traffic volumes shown for three-lane roads can be attained in only two of the three lanes. In the case of four-lane roads, however, it is possible to attain the volumes as shown by figure 3 in each of the traffic lanes during the same time period.**

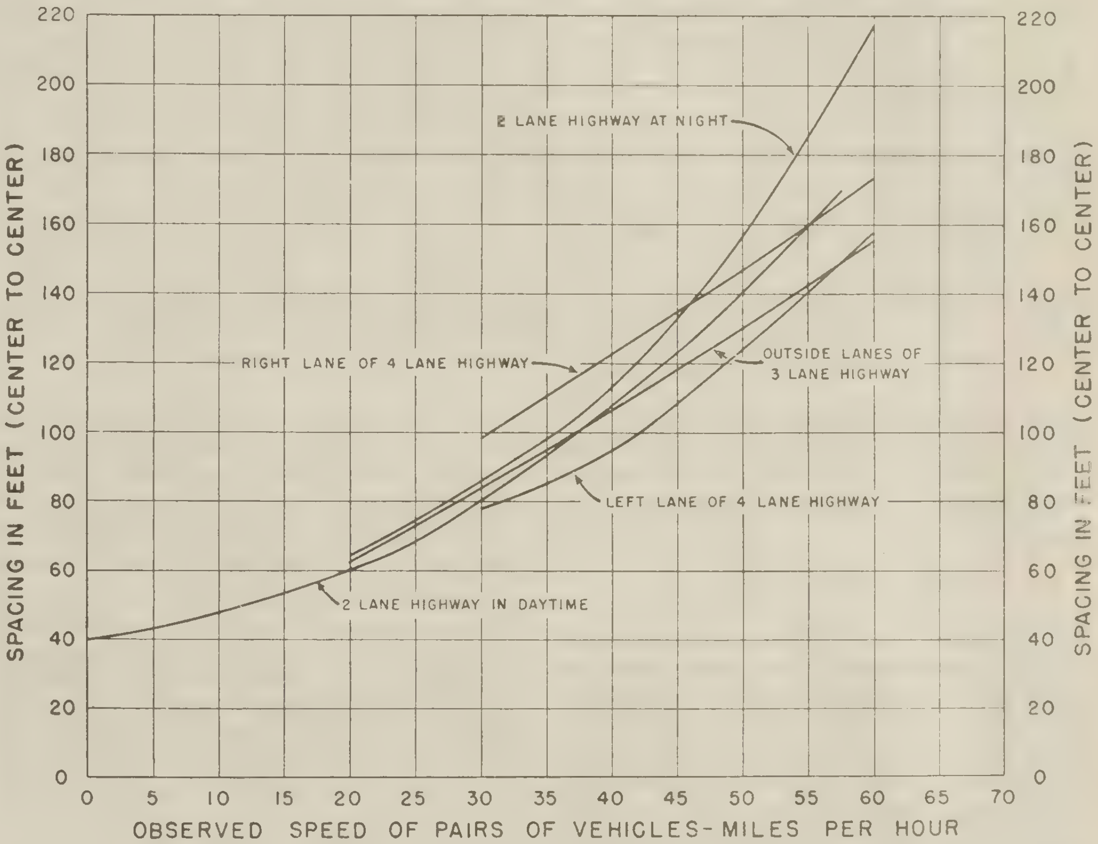


Figure 2.—Minimum spacings allowed by the average driver when trailing another vehicle, at various speeds.

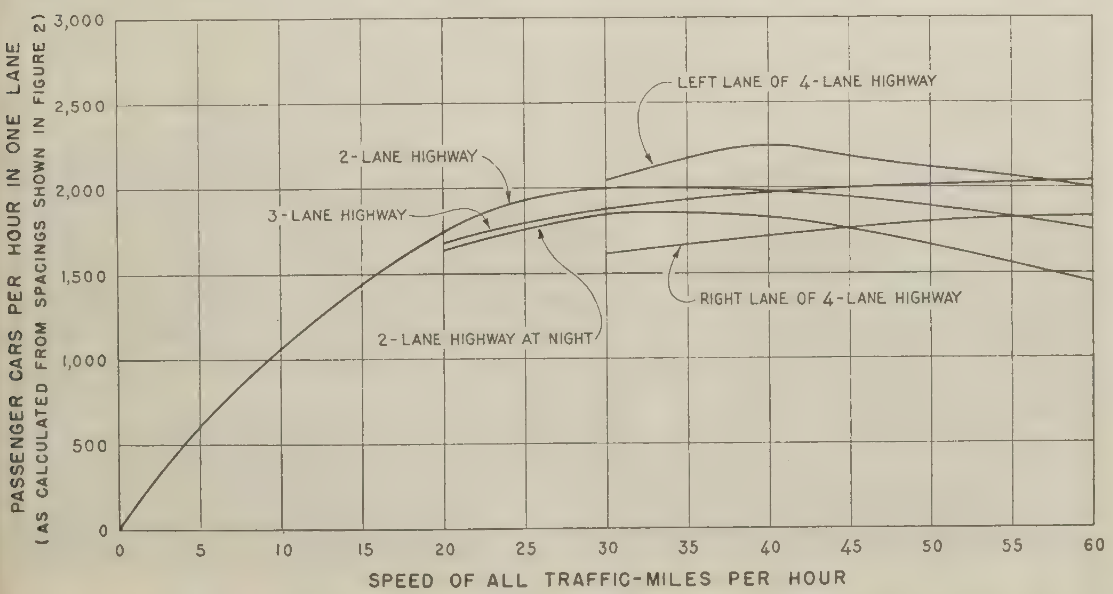


Figure 3.—Maximum capacity of a traffic lane, based on average spacings between pairs of vehicles traveling at the same speed.

The relation between average speed and traffic volume as shown by figure 3 holds true in actual practice. **The highest volumes per lane occur on roads where vehicles travel between 30 and 40 miles per hour at the time the roads are accommodating their maximum possible capacities.** For example, a two-lane road that handles its highest possible capacity when the vehicles are traveling 15 miles per hour will have only three-fourths the capacity of a road that handles its possible capacity at 30 miles per hour. Likewise, the road that handles its possible capacity at 30 miles per hour will only be able to handle half as much traffic whenever some abnormal condition causes the drivers to reduce their speeds to 9 miles per hour. **Any traffic variable or any**

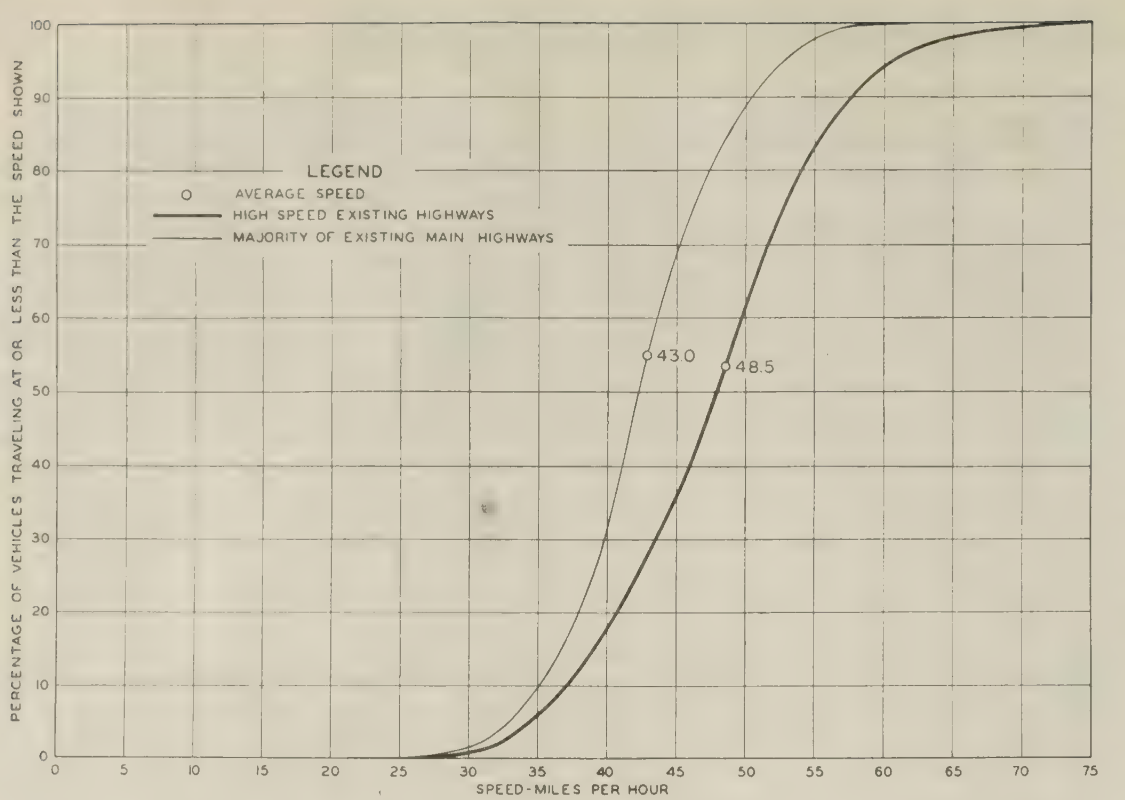


Figure 4.—Frequency distribution of travel speeds of free-moving vehicles on level, tangent sections of two-lane rural highways.

roadway condition that prevents vehicles from moving safely at a speed of 30 miles per hour lowers a roadway's capacity. A traffic density exceeding the critical density is one of these conditions.

Drivers' Desired Speeds

Drivers are influenced in the selection of their vehicular speeds by a large number of variables, such as the condition of the surface, the traffic density, the length of trip, the condition of their cars, and their own individual idiosyncrasies. **When traffic and roadway conditions are such that drivers can travel at whatever speed they desire, there is always a wide range in the speeds at which the various individuals operate their cars.** This fact is illustrated by the typical speed distribution curves shown in figure 4.

Average speeds higher than those shown in figure 4 have been recorded, particularly on rural multilane highways in the West and Midwest, and at one location an average speed of 58 miles per hour for passenger cars has been reported. **It is uncommon, however, for the average speed to exceed 50 miles per hour even during very light traffic densities.** Regardless of what the average speed may be, the general shape of the speed distribution curve for free-moving vehicles will be about the same as for the curves shown in figure 4. **It is evident from this information that comparatively few passenger-car drivers desire to travel at speeds which equal or approach the potential speeds of their vehicles even under the most favorable highway and traffic conditions.**

Effect of Traffic Volume on Speed

Prior to the development of equipment for accurately measuring the relation between speed and traffic volume, it was commonly assumed that at some traffic volume below the possible capacity of the street or highway a slight increase in traffic volume would cause a marked reduction in the average vehicle speed. Had this assumption been correct, it would have provided an ideal criterion by which to determine practical capacities. **Investigations conducted on an extensive scale have definitely shown, however, that there is a straight-line relation between traffic volume and average speed when other conditions are identical and the critical traffic density is not exceeded.** Figure 5 shows this relation for two typical rural conditions. The same relation between average speed and traffic volume is applicable to routes through cities, including streets with traffic signals, provided that the traffic densities do not exceed those that occur when the facility is accommodating its possible capacity and provided also that other influencing factors are constant.

When the average speed is reduced as a consequence of an increase in traffic volume, the speed distributions change in the manner shown by figure 6, which illustrates conditions observed on a typical high-speed highway. This set of curves shows that **when the distribution of speeds and the average speed are known for a particular traffic volume on a given route, it is possible to predict with a high degree of accuracy the speed distributions for other average speeds.**

Difference in Speed a Criterion of Possible Capacity

The range in the speeds of individual vehicles, at a point where the traffic flow is not interrupted by traffic signals, decreases with an increase in traffic volume as shown by figure 6. With little traffic on the highway, drivers travel at their desired speeds. As the traffic volume increases, individual drivers are affected more and more by other traffic. The high-speed drivers obviously are affected to a greater degree than the lower-speed drivers. **When the traffic volume becomes high enough to prevent the high-speed drivers from passing the low-speed drivers, all traffic must move at approximately the same speed and the average difference in speed between successive vehicles will approach or become zero. When this occurs, the traffic volume has reached the possible capacity of the particular facility under the prevailing conditions and the number of vehicles per unit length of highway will**

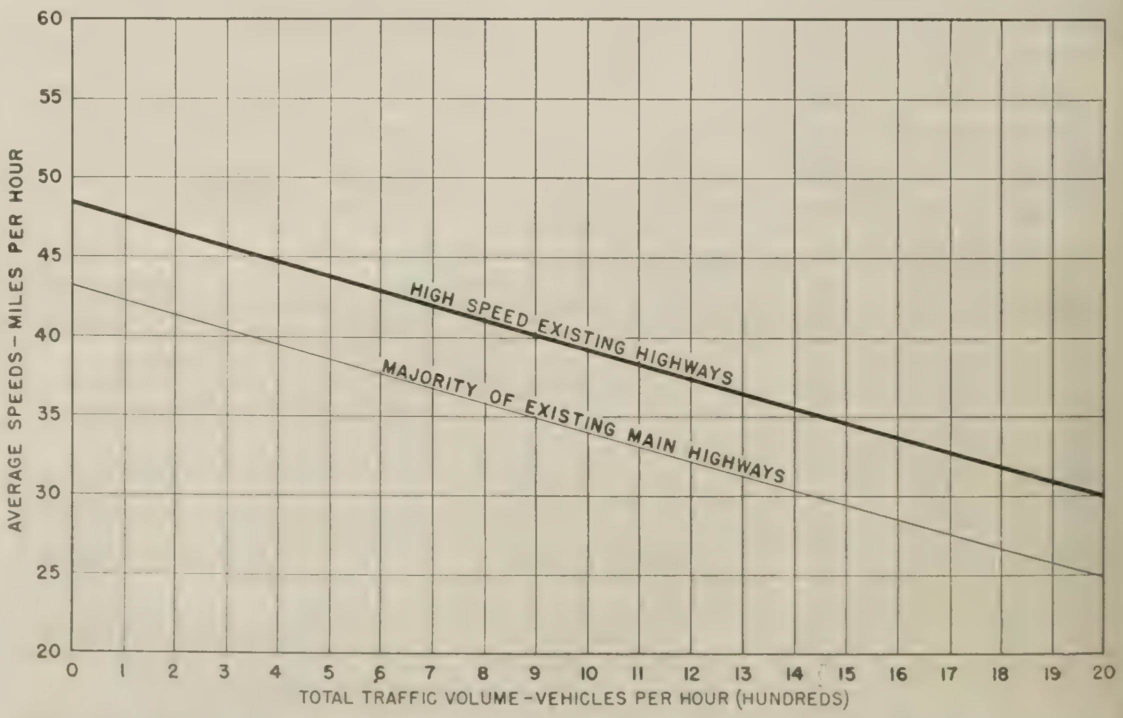


Figure 5.—Average speeds of all vehicles on level, tangent sections of two-lane rural highways.

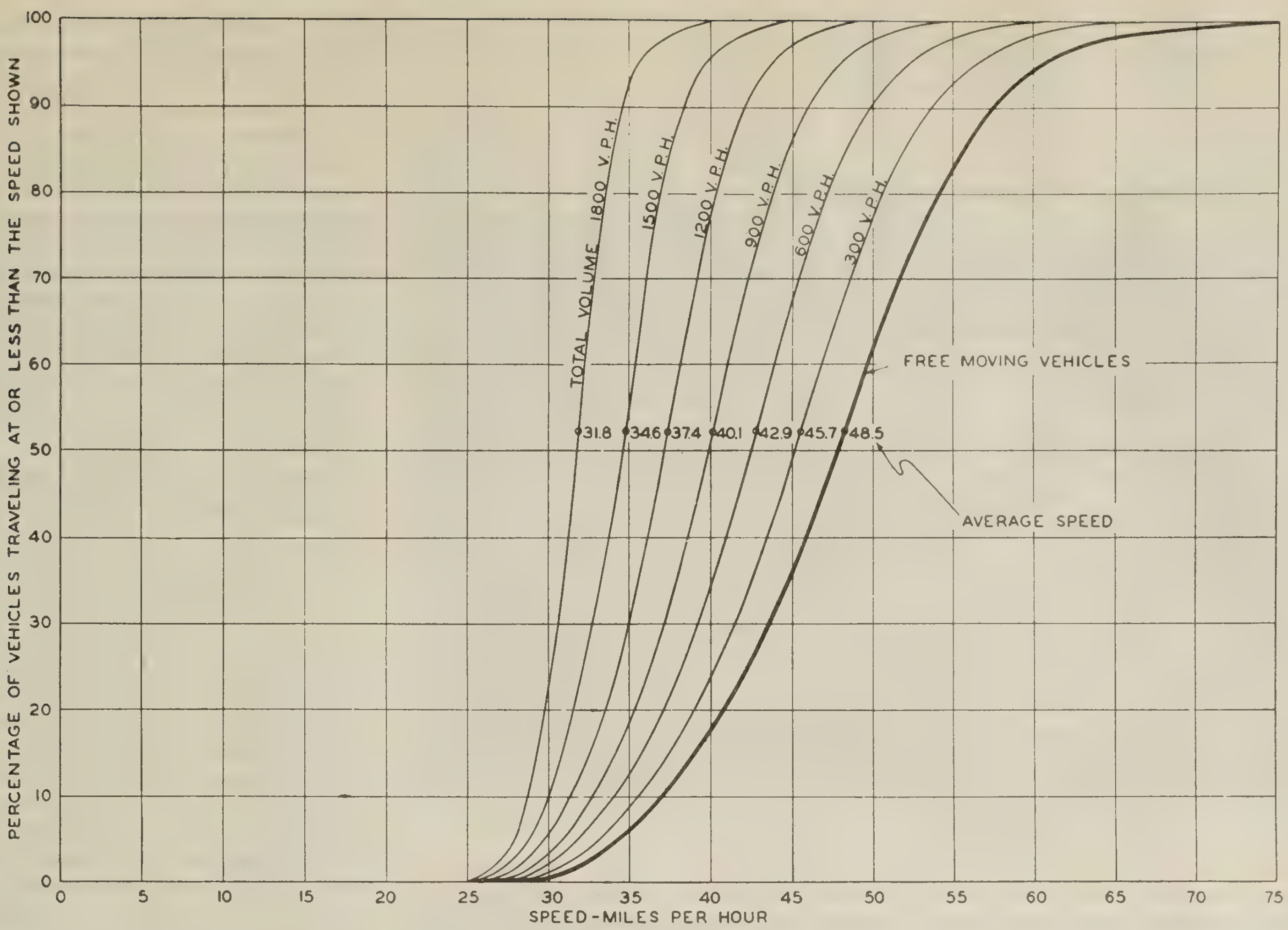


Figure 6.—Typical speed distributions at various traffic volumes on level, tangent sections of two-lane, high-speed existing highways.

then equal the critical density for that highway. If the traffic density continues to increase there will be a marked reduction in speed with the result that the traffic volume, which is the product of the density and the speed, will be lowered below the highway's possible capacity.

Extensive studies have shown that on facilities where drivers are not influenced by speed limits, **the average difference in speed between successive vehicles decreases as a straight line relation with an increase in traffic volume until the traffic volume reaches the facility's possible capacity at the critical density.** This finding has made it possible to determine the effect that various highway features and traffic conditions have on the possible capacities of different types of highway facilities. It is also possible to predict, with a high degree of accuracy, the capacity of a particular facility without waiting until that facility becomes congested. This is accomplished by plotting the average difference in speed during a very low traffic density and during a somewhat higher traffic density on a graph, using the traffic volume and the mean difference in speed between successive vehicles as the coordinate scales. A straight line going through these points and extended to the point at which the speed difference is zero will indicate the traffic volume representing the possible capacity.

Vehicles stopped or standing on the pavement not only deprive other traffic of a usable portion of the roadway, but by causing a reduction in speed of traffic they lower the capacity of the remaining lanes.

Turn-out lanes permit busses to stop with little or no interference with other traffic. This one might well have been a little wider.

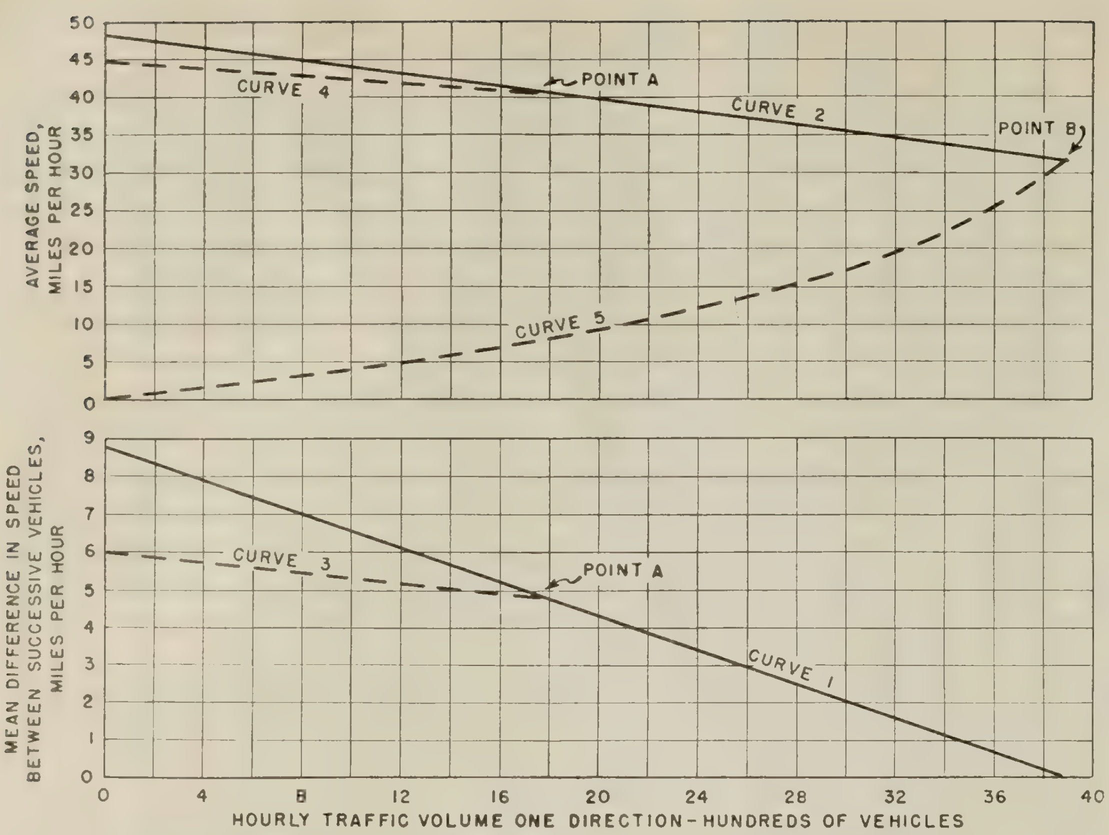


Figure 7.—Speeds and speed differences on a typical four-lane divided highway.

When calculating the mean difference in speed between successive vehicles, the speeds of individual vehicles are first separated by direction of travel and then arranged in the same order as that in which the vehicles passed a given point on the highway, regardless of the number of lanes for each direction of travel. The difference in speed is then calculated for pairs of vehicles using each vehicle first as the following vehicle and then as the leading vehicle. The differences are then averaged arithmetically, disregarding the algebraic signs.

For two-way, two- and three-lane roads, the means for the two directions are averaged by weighting according to the number of vehicles in each direction of travel. For multilane highways, the mean difference in speed for one direction of travel is never combined with the corresponding value for the other direction because the resulting figure would be meaningless.

Relation Between Speed and Traffic Volume

The cause of traffic "tie-ups" or the sudden occurrence of complete congestion on a facility can be explained by employing the average difference in speed in combination with the relation between speed and volume as shown by figures 3 and 5. The change in the average speed and the change in the mean difference in speed between successive vehicles with an increase in traffic volume on a typical four-lane divided highway without a speed limit are shown by the solid lines of figure 7. Curve 1 shows that the average difference in speed between successive vehicles decreases as a straight line with an increase in traffic volume until at a total volume in one direction of 3,900 vehicles per hour, the possible capacity of the two lanes, all vehicles are moving at the same speed.

Curve 2 shows that the average speed also decreases from 48.5 to 32 miles per hour with the traffic volume increasing to 3,900 vehicles per hour. On similar highways with an enforced speed limit of 50 miles per hour the average speeds and the mean difference between the speeds of successive vehicles for the low traffic volumes would be as shown by curves 3 and 4. That is, for volumes under 1,750 vehicles per hour, the speed limit would have a greater effect on speeds than would the traffic densities.

Possible Range of Speeds for Each Volume

Curve 5 is based on the combined volumes of the two curves shown in figure 3 for four-lane highways. It represents the lowest possible speed of traffic if the two lanes are to accommodate the various total traffic volumes. For example, with a total volume of 2,000 vehicles per hour in the one direction, the average speed of traffic could be anywhere between 10 and 40 miles per hour. With an average of 40 miles per hour, there would be a wide distribution of speeds, whereas if the average were 10 miles per hour all vehicles would be moving at approximately the same speed. Should some condition cause traffic to slow to less than 10 miles per hour, the traffic capacity of the highway would become less than 2,000 vehicles per hour and traffic would immediately become badly congested. The intersection of curve 5 with curve 2 at point *B* represents the maximum possible capacity of the roadway under the prevailing conditions and is the maximum volume that can occur with a zero difference in speed between successive vehicles. The distance between curves 2 and 5 is a direct measure of the range in average speeds that can occur at the different total traffic volumes. The various distances are therefore a relative measure of the safety factor present to prevent the occurrence of complete traffic stagnation. Any point representing the relation between speed and volume must fall within the area between these two curves.

Traffic Volume Below Possible Capacity When Critical Density is Exceeded

To understand why complete congestion so often occurs when a highway is operating at or near its possible capacity, assume that traffic on the road which figure 7 represents has gradually increased to a volume of 3,900 vehicles per hour at an average speed of 32 miles per hour. Assume also that this traffic volume is approaching a point on the highway where drivers suddenly reduce their speeds to 20 miles per hour because vehicles are entering from a side street. The capacity of the highway at the point where speeds are only 20 miles per hour cannot exceed 3,250 vehicles per hour as shown by curve 5. Under this condition, vehicles would immediately start to accumulate at this point on the highway at the rate of 650 per hour, causing a sudden increase in the density of traffic. If the approach volume of 3,900 vehicles per hour and the restricted condition existed for only a few seconds, some vehicles would be required to stop and the traffic volume would immediately drop to zero at this point on the highway, as shown by curve 5. The queue of vehicles at a standstill would continue to increase in length until the volume of approaching traffic dropped to no more than 3,250 vehicles per hour and probably not until the approaching volume had dropped to 3,000 vehicles per hour. (One vehicle every 2.4 seconds has been found to be the average rate at which consecutive vehicles stopped in line get started again when there is an open road ahead.)

Even though the cause of the restriction lasts but a few seconds or minutes, additional vehicles might continue to become stopped for a considerable time after the cause of the restriction had been removed. These vehicles would form a queue which would move down the highway in the direction opposite to that of traffic flow. Queues of vehicles at a standstill have been observed on the Oakland-Bay Bridge and the Pulaski Skyway several miles from the scene of the original restriction, even though traffic was apparently operating in its normal manner between the queue and the place where the queue originally started to form.

Part IV.—Roadway Capacities for Uninterrupted Flow

INTRODUCTION

A logical sequence for presenting the available capacity material would consist of reporting the highest traffic capacities attainable under ideal conditions and then showing, by successive steps, the quantitative extent to which various traffic and roadway conditions affect these ultimate capacity values. That is the procedure followed in this chapter. Basic capacities are presented for the three general classes of highways: two-lane, three-lane, and multilane. Possible capacities are then discussed, and finally a suggested procedure is outlined for arriving at practical capacities for roads of all descriptions where the movement of traffic is uninterrupted by intersections or junctions.

As a source of information for this report, results are available from studies conducted by many individuals and organizations; in particular, those for the comprehensive studies of the dynamics of highway movement conducted by the Bureau of Public Roads in cooperation with State highway departments in all sections of the country. The data obtained and analyzed by the Bureau of Public Roads alone include detailed information such as individual vehicle speeds and spacings between vehicles under actual operating conditions at approximately 500 locations. During the periods of study at these locations traffic increased from comparatively low densities to the peak densities and then decreased to a low level again. By the use of special electro-mechanical equipment designed and built especially for this purpose, detailed data for slightly over a million vehicles have been recorded during the past 10 years for many of the most heavily traveled roads in the country.

The results of these studies have been supplemented by investigations of motortruck performance, including grade-climbing ability and braking or stopping distances; studies of the driving characteristics of various classes of motor-vehicle operators; studies of passing practices on two-lane roads in which detailed information was recorded for nearly 20,000 passing maneuvers; and studies of the effect on traffic behavior of various types of pavement markings and other control devices. These studies are in addition to the periodic speed studies made by the State highway departments, which have included speed observations on 2 million vehicles at 787 locations since 1939, and the traffic counts made manually and by hourly recording electrical counters for the purpose of obtaining annual and peak volumes on all main highways throughout the United States.

The severe congestion here illustrated resulted from an emergency stop of one vehicle on the bridge in background.

BASIC CAPACITIES

The uninterrupted flow of traffic may generally occur only on urban freeway facilities and on the sections of rural highway that are removed from the influence of intersections at grade. Even on these facilities, however, certain traffic and roadway conditions can cause an interruption of the normal traffic flow. It is nevertheless essential in a study of highway capacity to know the capacity of a facility for conditions of uninterrupted flow in order that proper deductions can be made for conditions that cause the flow to be interrupted.

Multilane Roads

The largest number of vehicles that can pass a point one behind the other in a single traffic lane, under the most ideal conditions that can possibly be attained, is between 2,000 and 2,200 passenger cars. So far as is known, hourly lane volumes within this range have been recorded at not more than two locations. Volumes only slightly over 2,000 vehicles per hour per lane have been recorded at several locations, but all reports of lane capacities in excess of 2,300 vehicles per hour have proved to be incorrect.

Traffic volumes in the neighborhood of 2,000 vehicles per lane per hour can occur only if the following five conditions are satisfied:

1. There are at least two lanes for the exclusive use of traffic traveling in one direction.
2. All vehicles move at approximately the same speed, each driver being restricted to the speed of the vehicle ahead. This speed, which is governed by the speed of the slowest drivers, must be between 30 and 40 miles per hour.
3. There are practically no commercial vehicles.
4. The width of traffic lanes, shoulders, and clearances to vertical obstructions beyond the edge of traffic lanes are adequate.
5. There are no restrictive sight distances, grades, improperly superelevated curves, intersections, or interferences by pedestrians.

Since these conditions can be satisfied on a multilane facility, the maximum number of passenger cars that can pass a given point during 1 hour under the most nearly ideal roadway and traffic conditions which can possibly be attained, or **the basic capacity of multilane roads, is 2,000 passenger cars per lane per hour.**

It has been rather widely assumed that the capacity of multilane facilities decreases with an increase in the number of lanes. This is not necessarily true. The Outer Drive in Chicago, for example, with its eight lanes, is one of the most efficient facilities. It has accommodated an average of 1,958 vehicles per lane per hour in the one direction of travel during several periods when manual counts were being conducted. The provision of adequate access and egress facilities such that the full capacity of all traffic lanes can be utilized, however, becomes increasingly difficult as the total number of lanes is increased.

Three-lane roads

On two- and three-lane roads there are not two lanes for the exclusive use of traffic traveling in the one direction. The character of operation is therefore entirely different on these roads from that on multilane highways, since vehicles performing passing maneuvers are forced to use a traffic lane that is provided for vehicles traveling in the opposite direction. Consequently, the basic capacities of two-

and three-lane roads are much lower than for multilane facilities.

When traffic on a three-lane highway is evenly divided by directions, when there are no restrictive sight distances, and when other conditions are ideal, vehicles can completely fill the two outside lanes by utilizing the center lane for passing, thus filling the long gaps that would otherwise occur between vehicles in the outside lanes ahead of slow-moving vehicles. Likewise, it is only when there is little or no traffic in the one direction that the one outside lane and the center lane can become filled with vehicles traveling in the other direction so that the characteristics of the flow may become similar to those in one direction on a four-lane highway. **The basic capacity of a three-lane, two-way road is therefore 4,000 passenger cars per hour or an average of 1,333 passenger cars per lane per hour. The basic capacity for one direction is limited to 2,000 passenger cars per hour on any section with but a single restrictive sight distance.**

Extensive studies have shown that there is no basis for the common assumption that most efficient operation on a three-lane road will be realized with approximately two-thirds of the traffic in one direction. Facts show that the high volumes can be handled most efficiently when traffic is evenly divided by direction, especially when there are passing sight-distance restrictions. As yet, the Committee has been unable to locate any count approaching 4,000 vehicles per hour on a three-lane road, and this is probably because there are sufficient sight-distance restrictions on most existing three-lane roads to prevent their basic capacities from being attained. A total count of 3,064 vehicles per hour has, however, been recorded on a three-lane road in New Jersey.

Two-Lane Roads

On a two-lane, two-way road, vehicles must, to overtake and pass vehicles traveling in the same direction, use the lane normally used by oncoming traffic. With few or no vehicles traveling in the one direction and no restrictive sight distances, traffic in the other direction can keep one lane completely filled because gaps that occur ahead of the slower-moving vehicles can almost immediately be filled by vehicles performing passing maneuvers. Whenever one vehicle traveling in the direction of the light flow appears, however, all vehicles traveling in the direction of the heavy movement must crowd into one traffic lane. Since the capacity of one traffic lane is limited to a maximum of about 2,000 passenger cars per hour, the basic capacity of the two-lane road under these conditions would be 2,000 passenger cars per hour.

With traffic evenly divided by directions, opportunities to overtake and pass slow-moving vehicles are sufficiently restricted by oncoming traffic to limit the flow in each direction to 1,000 passenger cars per hour. At this traffic volume, spaces occur ahead of the slow-moving vehicles which cannot be filled by other vehicles performing passing maneuvers. In effect, traffic in both directions tends to form in queues which continue to increase in length until the spaces between the queues become sufficiently long to permit the performance of passing maneuvers. As soon as a few passing maneuvers are performed, the spaces between the queues become partially occupied and are no longer of sufficient length for the performance of passing maneuvers, and the queues immediately start forming again.

This accordion effect, with all but a very limited number of vehicles traveling at the same speed as the vehicle immediately ahead, occurs at the same total traffic volume regardless of the distribution by directions. **The basic capacity of a two-lane, two-way road is therefore a total of 2,000 passenger cars per hour regardless of the distribution by directions.**

Total traffic volumes close to 2,000 vehicles per hour have been recorded on two-lane, two-way facilities during periods when most of the traffic traveled in the one direction and also during periods when the traffic was evenly divided by direction. In only three cases have two-lane, two-way facilities been reported to have accommodated somewhat more than 2,000 vehicles in 1 hour. These occurred at tunnels where the comparatively short two-lane roadway sections were bottlenecks between higher-capacity facilities.

POSSIBLE CAPACITIES

When roadway and traffic conditions are ideal, the possible capacity of a facility with uninterrupted flow corresponds to its basic capacity. **Since roadway and traffic conditions are seldom ideal, the possible capacity of a facility, or the maximum number of vehicles that can pass a given point on a lane or roadway during 1 hour under the prevailing roadway and traffic conditions, is generally lower than its basic capacity.**

In practice, the only application of a roadway's **basic capacity** is that it forms a starting point from which its possible capacity can be estimated or calculated by deducting the effect of the prevailing conditions which are not ideal, whereas the **possible capacity** is a positive quantity that has a direct application to many problems with which the engineer is faced.

In the discussion of practical capacities, there are listed a number of the more important factors that influence traffic capacities when the flow is uninterrupted. **The resulting effect that these factors have on traffic capacity must be subtracted from the basic capacities to obtain the possible capacities for the prevailing conditions.**

PRACTICAL CAPACITIES

All vehicles must move at approximately the same speed when a street or highway is operating at its possible capacity, each driver being restricted by the speed of the vehicle ahead, which is usually the speed of the slowest group of drivers. Under this condition most drivers consider a highway extremely congested, because most of them want to travel faster than the slowest group, and they desire some freedom in the selection of their individual speeds. The average vehicle speed on a highway operating at or near its possible capacity is lower than the speed which most drivers consider reasonable.

Criteria of Practical Capacities Under Ideal Conditions

The practical capacity of a highway carrying an uninterrupted flow of traffic is reached when a higher volume will cause drivers to be unreasonably restricted. "Unreasonably re-

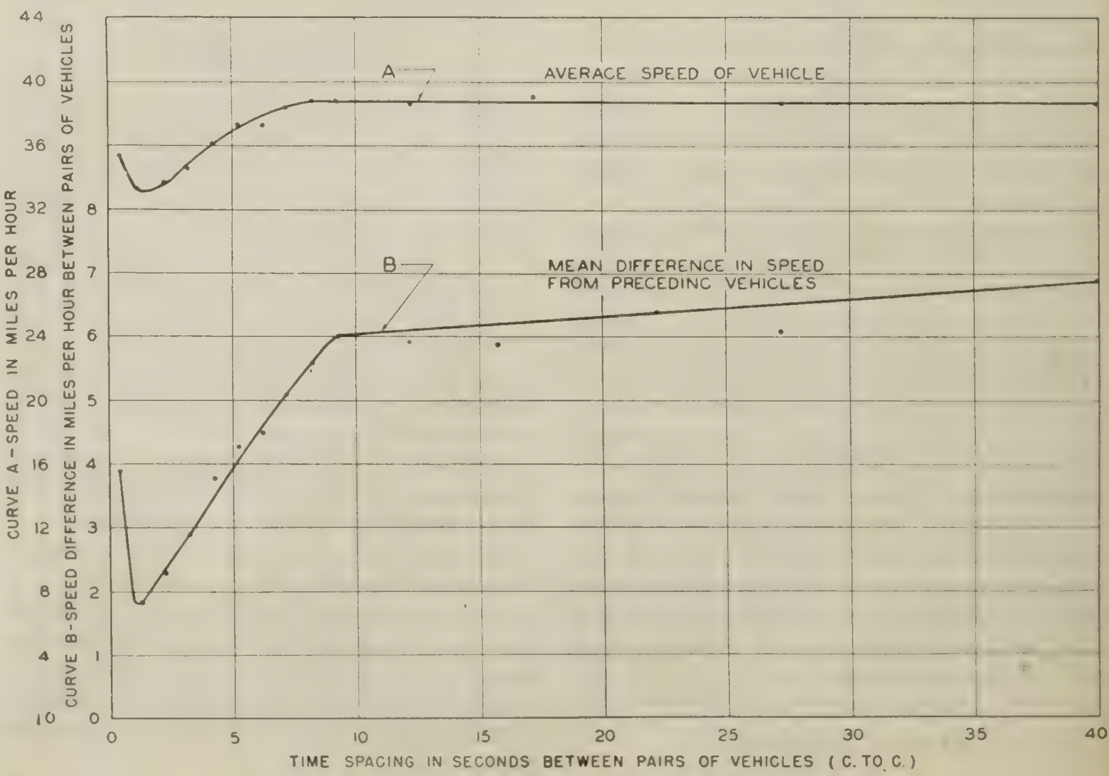


Figure 8.—Speed characteristics of vehicles traveling at given time spacings behind preceding vehicles.

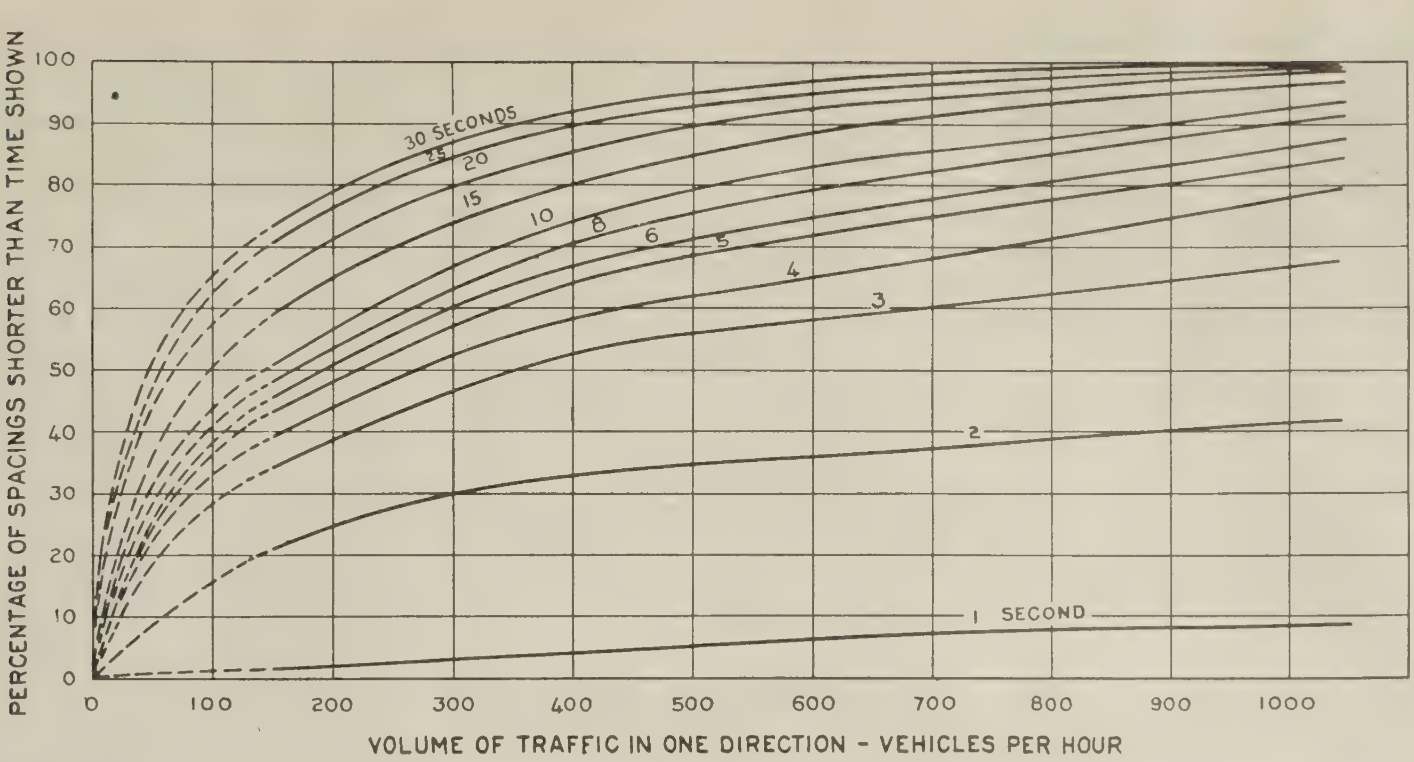


Figure 9.—Frequency distribution of time spacings between successive vehicles, at varying volumes of traffic on a typical two-lane rural highway.

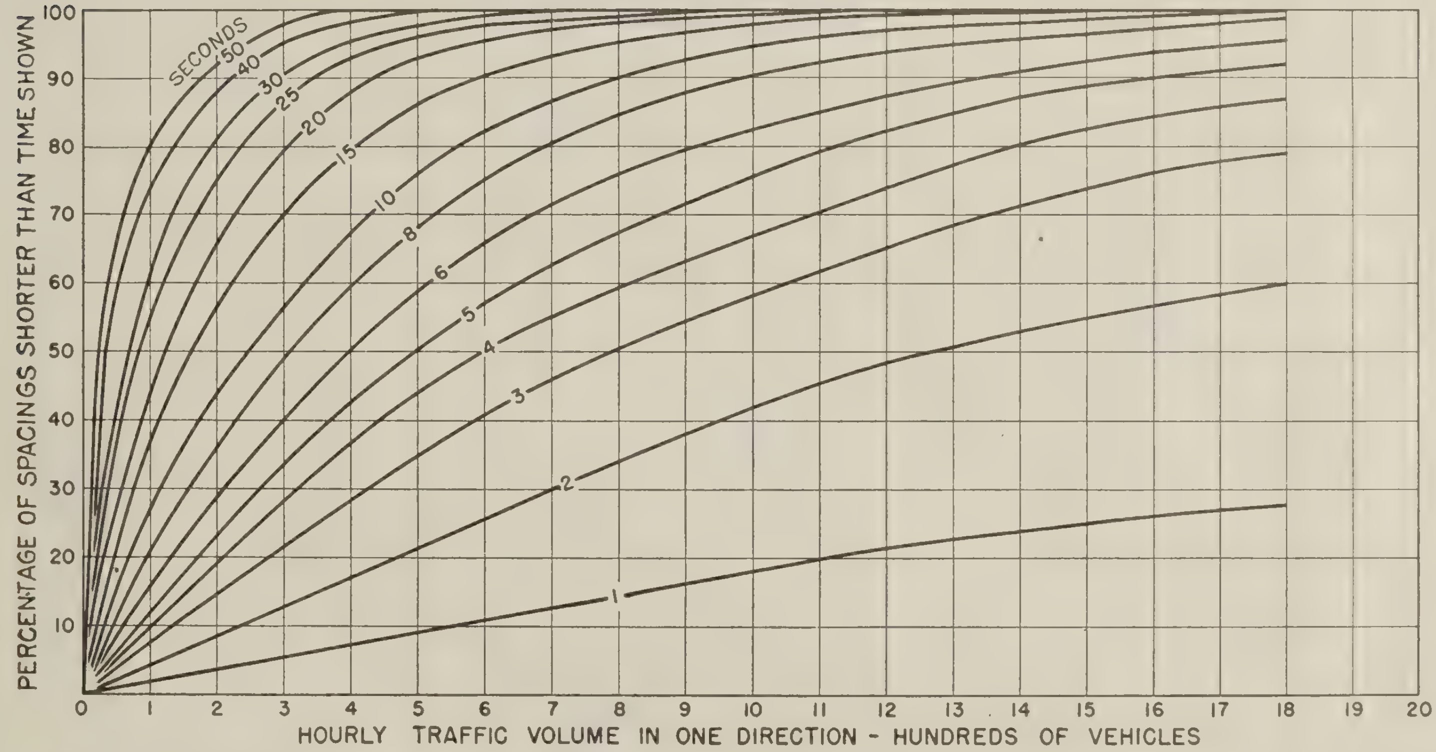


Figure 10.—Frequency distribution of time spacings between successive vehicles traveling in the same direction, at various traffic volumes on a typical four-lane rural highway.

stricted" is only a relative term which will vary for different locations. In urban areas, for example, a driver is willing to accept the regulation of his speed by other traffic to a greater extent than in rural areas, so long as he can keep moving at a speed he considers reasonable under the circumstances. Furthermore, **the relative restriction and the average travel time will increase uniformly as the traffic volume on a highway is increased from low volumes to the maximum possible capacity of the highway. There is no volume, below the highway's maximum capacity, at which a further increase in volume will cause a marked increase in congestion or decrease in speed.** This has been illustrated by figures 5 and 7. It is necessary, therefore, to apply other criteria which have been developed to measure congestion in the selection of practical capacities for various conditions.

Vehicle spacings

The most sensitive index of traffic congestion on two-lane highways is shown in figure 8 (curve *B*). This figure shows that as the spacing between vehicles decreases there is little change in the difference in speed of successive vehicles until the time spacing is reduced to 9 seconds. Below that spacing, the speed of the following vehicle approaches that of the one ahead very rapidly, indicating that with a spacing of 9 seconds, drivers are affected by the presence of the car ahead, and that the shorter these spaces become the greater is the effect.

If all vehicles using a highway were equally spaced, determination of the point of incipient congestion would be a simple matter. However, it is a well-known fact that vehicles do not move with uniform separating intervals, but rather that they tend to form groups. Studies made on tangent highway sections in

A section of two-lane road where the design features are ideal for high capacity.

many parts of the country show that this tendency to form groups is remarkably uniform regardless of the traffic volume. Figures 9 and 10 are typical of the vehicle-spacing distributions for conditions where the flow of traffic is uninterrupted.

Under nearly any conditions of speed and traffic volume, approximately two-thirds of the vehicles will be spaced at, or less than, the average distance between vehicles. Using figure 9, the curve of vehicle spacings on two-lane roads, it will be found, for example, that with an hourly volume of 180 vehicles in one direction (representing an average spacing of 20 seconds) about 120 vehicles will be 20 seconds or less behind the car ahead, and of these about 90, or 52 percent of the total, will be spaced at 9 seconds or less and will therefore be affected to some degree by the car ahead. As the traffic volume increases, the number so spaced increases. With 200 vehicles per hour in one direction, 55 percent will feel some effects of congestion; with 300 vehicles per hour the figure becomes 65 percent; with 400 it becomes 72 percent, and so on until over 90 percent of the vehicles are affected when the volume becomes 1,000 vehicles per hour in each direction.

If it be considered that a highway is congested when 72 percent of the drivers must govern their speeds by the speeds of other vehicles, 800 vehicles per hour is the practical capacity of a two-lane road.

Passing opportunities

Another index of congestion is the availability of opportunities for vehicles to overtake and pass slower vehicles moving in the same direction. If the alinement of a highway is not a factor, passing on a two-lane road is limited only by the time the lane normally used by oncoming traffic is occupied. The ratio of the number of passings required per mile of highway for drivers to maintain their desired speeds, to the number of passings that they can actually perform, is a measure of traffic congestion. Figure 11 compares the desired number of passings with the actual number that can be performed under typical conditions on a two-lane road with tangent alinement.

The total number of passings required for all drivers to maintain their desired speed increases as the square of the traffic volume. Actually, however, the total number of passings that occur increases with an increase in the total traffic volume up to 1,300 vehicles per hour and then decreases rapidly. To maintain his free speed, the number of passings each driver would make increases directly as the traffic volume increases. Actually, however, **the number of passings made by the average driver increases as the density increases up to 800 vehicles per hour, remains about the same between 800 and 1,200 vehicles per hour, and thereafter decreases with a further increase in the traffic density. The fact that the average driver on a two-lane, tangent highway should increase the number of passings he makes as the traffic volume goes above 800 vehicles per hour, but can make no material increase due**

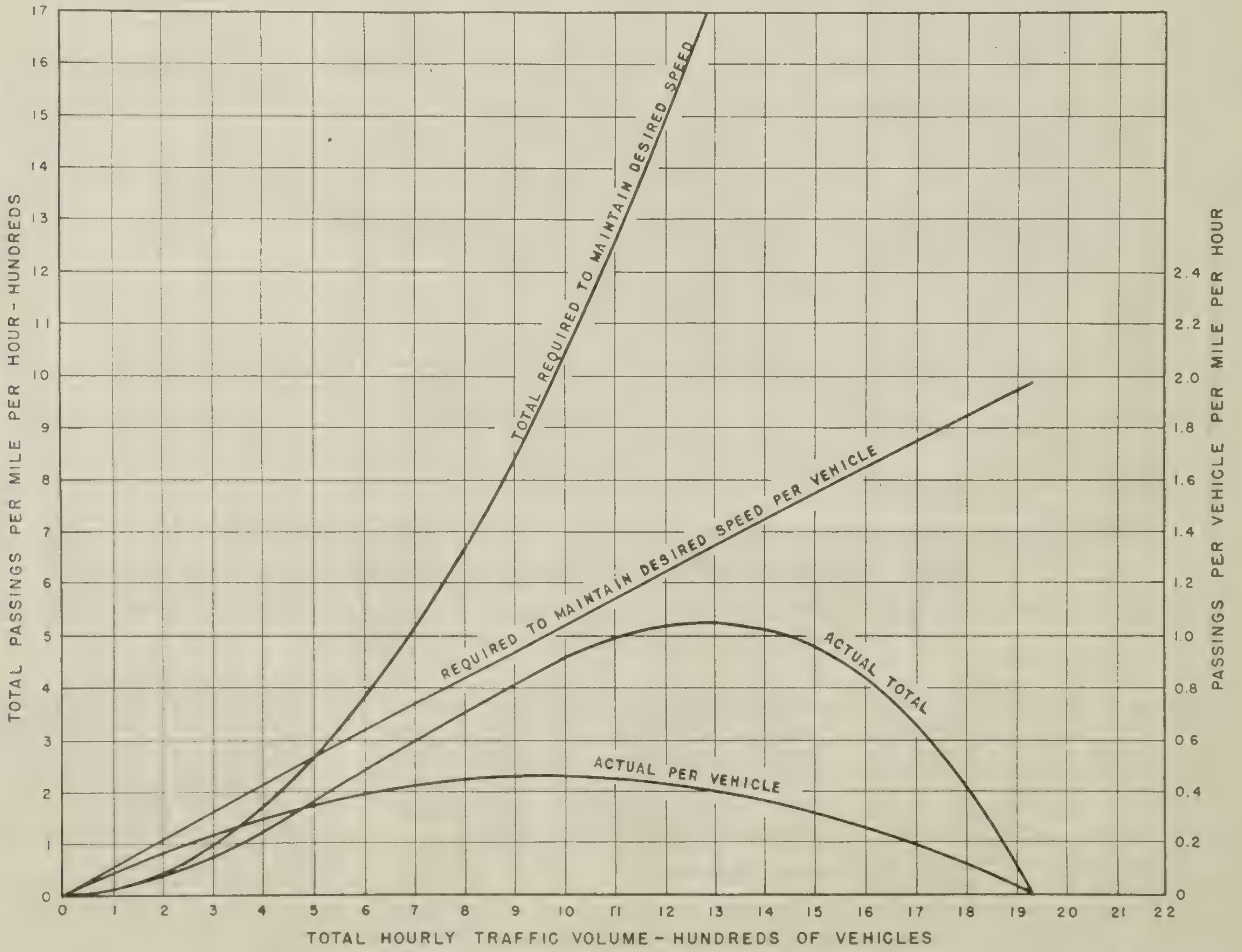


Figure 11.—Comparison of actual number of passings performed and number that would be required at various traffic volumes for all vehicles to maintain their free speed on a two-lane highway with two-thirds of the total traffic in one direction.

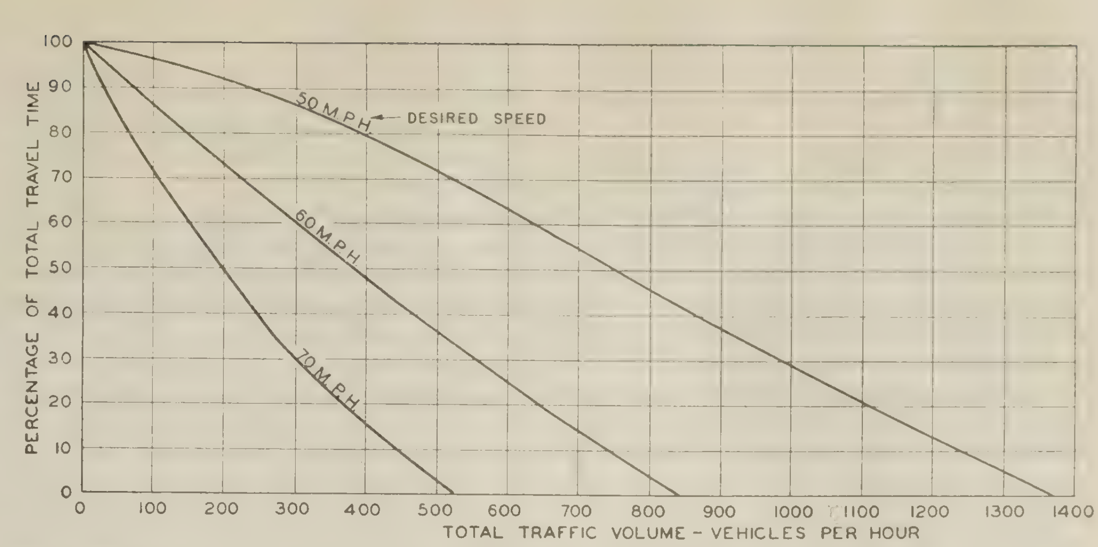


Figure 12.—Percentage of time that desired speed can be maintained on two-lane, level highway with no restrictive sight distances.

to the traffic density, is a very important criterion in the determination of practical capacities for two-lane highways. (A traffic volume of 800 vehicles per hour with the normal percentage of commercial vehicles is equivalent to 900 passenger cars per hour.)

Operating speeds

The most significant index of traffic congestion during different traffic volumes, as far as drivers are concerned, is the over-all speed (exclusive of stops) which an average motorist can maintain when trying to travel at the highest safe speed. This over-all speed is termed the "operating speed."

A driver on a two-lane, tangent highway can travel at a uniform speed of say 50 miles per hour, until he overtakes a slower-moving vehicle. He would then either pass the slower vehicle, if there was no oncoming traffic, or he would slow down to the speed of the vehicle ahead and wait until the opportunity to pass presented itself. For a driver to travel at a uniform speed of 50 m.p.h. on a modern two-lane highway carrying a total of 300 vehicles per hour equally divided in each direction, he would be required to pass an average of 24 vehicles per hour. At a volume of 900 vehicles per hour he would be required to pass 130 vehicles per hour. In the first case, 43 percent of the vehicles he passed would be traveling at speeds exceeding 40 m.p.h. while in the second case only 23 percent of the vehicles he passed would be exceeding 40 m.p.h.

Under actual operating conditions on a two-lane highway, the left lane would not always be free of oncoming traffic at the time the driver overtook a vehicle traveling at a slower speed, so even on highways with no sight-distance restrictions, he would sometimes be forced to reduce his speed and await an opportunity to pass. This delay would cause a decrease in his average speed which in turn would decrease the number of vehicles overtaken within a given time period.

Figure 12 shows the portions of the total time that a driver desiring to travel at a certain speed can travel at that speed on a two-lane highway with no sight-distance restrictions. A driver desiring to travel at 70 m.p.h. can travel at this speed 100 percent of the time as long as there is no other traffic on the highway. However, when there is other traffic on the highway, he soon overtakes another vehicle traveling at a slower speed and, unless there is a space between vehicles in the opposing traffic lane of sufficient length to permit him to pass, he must reduce his speed until such an opportunity does occur, after which he can again increase his speed to 70 m.p.h. At a total traffic volume of 200 vehicles per hour, it will be possible for the driver to travel at 70 m.p.h. 50 percent of the time if he takes full advantage of his opportunities to pass the slower drivers. At a traffic volume of about 550 vehicles per hour he will not be able to travel at 70 m.p.h. any of the time because after passing one vehicle he must start slowing down to avoid a rear-end

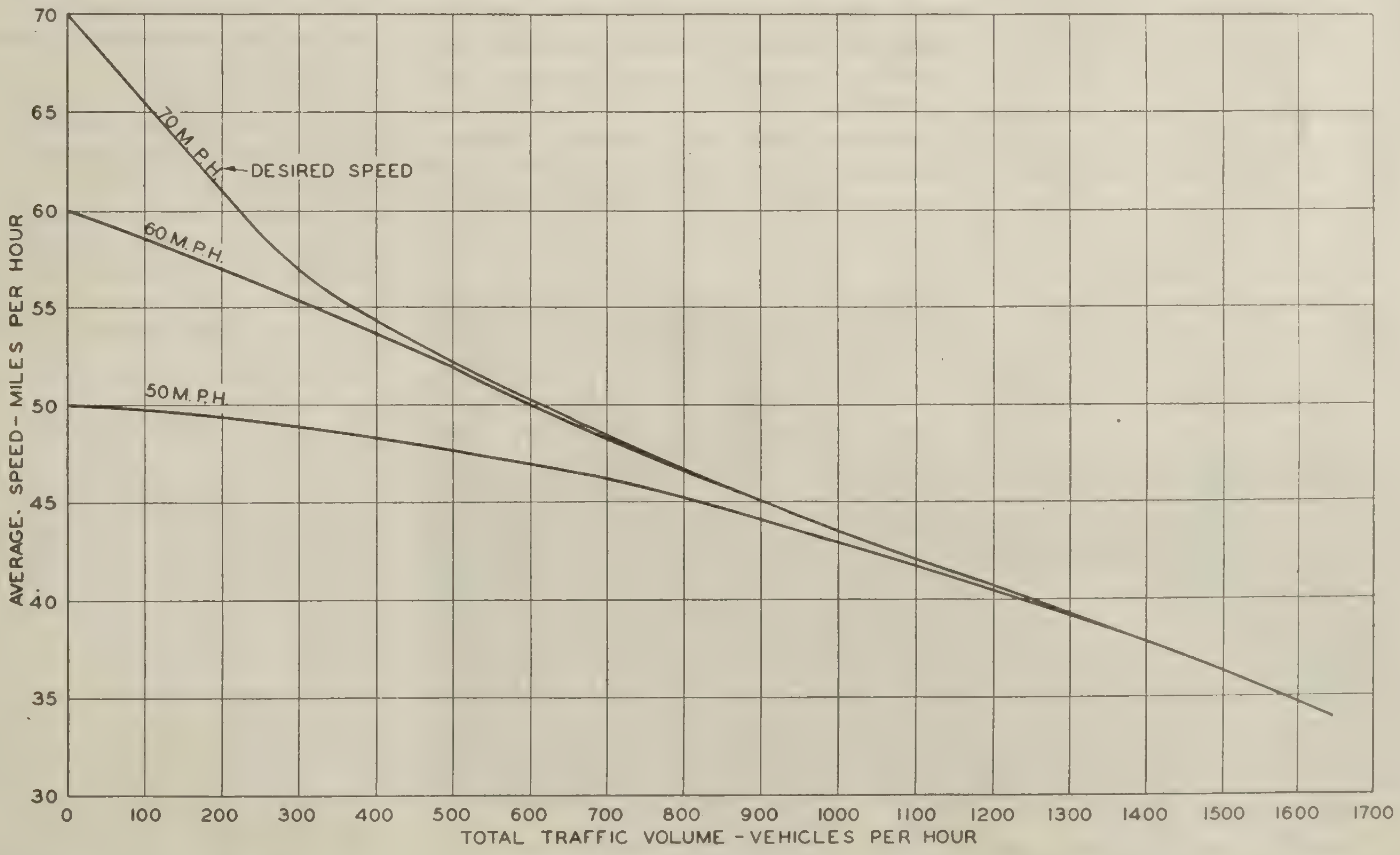


Figure 13.—Average speeds for drivers traveling at their desired speeds whenever possible on a two-lane, level highway with no restrictive sight distances.

collision with the preceding vehicle traveling in the same direction or a head-on collision with oncoming traffic in the opposing traffic lane.

Likewise, a driver trying to travel 60 m.p.h. can maintain this speed 100 percent of the time when there is no other traffic, and 50 percent of the time when the traffic volume is 400 vehicles per hour, but he cannot at any time attain this speed when the traffic volume is in excess of 850 vehicles per hour. Also, a driver trying to maintain a speed of 50 m.p.h. can accomplish this 50 percent of the time with a traffic volume of 750 vehicles per hour but at no time can he travel at this speed when the traffic volume exceeds 1,400 vehicles per hour.

These curves in figure 12 also show the percentage of time that drivers must travel at various speeds below their desired speeds. For example, with a traffic volume of 400 vehicles per hour, a driver whose desired speed is 70 m.p.h. can travel at this speed 15 percent of the time; between 70 and 60 m.p.h., 35 percent of the time; between 60 and 50 m.p.h., 30 percent of the time; and is required to reduce his speed below 50 m.p.h. about 20 percent of the time.

A driver trying to go 70 m.p.h. can travel no faster than a driver trying to go 60 m.p.h. when the traffic volume exceeds 850 vehicles per hour. The 60- and 70-m.p.h. drivers can go no faster than the 50-m.p.h. driver when the traffic volume exceeds 1,400 vehicles per hour.

Effect of other traffic

Figure 13 shows the effect of other traffic on the over-all speed of drivers trying to maintain a certain desired speed. On tangent sections of existing high-speed, two-lane highways, a driver trying to maintain a speed of 70 m.p.h. without exceeding this speed finds that his over-all speed decreases rapidly with an increase in the traffic density. At a traffic volume of 200 vehicles per hour his over-all speed is reduced from 70 to 61 m.p.h. due to delays while waiting to pass slower-moving vehicles, and at 850 vehicles per hour his over-all speed will be 46 m.p.h. or the same as that for a driver trying to maintain a speed of 60 m.p.h. For all practical purposes the speeds for the 60- and 70-m.p.h. drivers are the same when the traffic volume is in excess of 300 vehicles per hour.

From these curves (fig. 13) it is possible to determine the hourly volume of traffic that can be accommodated by a two-lane highway at any specified operating speed when sight-distance restrictions are not a factor. If, for example, a two-lane road must accommodate peak volumes of 1,000 vehicles, the operating speed on that two-lane road, if it has no sight-distance restrictions, will be about 43 m.p.h. during periods that the peak volumes occur. It is possible from the results of these traffic studies to predict with a high degree of accuracy the operating conditions that will prevail with any given traffic volume on a highway with two, three, or four lanes where the flow is uninterrupted and other conditions are ideal. To determine the practical capacity of a facility it is necessary, first, to determine the operating conditions that the majority of motorists will accept as satisfactory. Then it is necessary to ascertain the highest standard of highway improvement that the governmental jurisdiction can support. Finally, it becomes necessary to reconcile the demands of the motorist with the means available for meeting these demands. Thus, in the final analysis, the matter of specifying precise values for practical highway capacities becomes a localized problem. **The Committee considers that it is of prime importance to relate traffic volumes accurately to operating conditions that will prevail so that individual agencies, with a thorough knowledge of the specific conditions, can decide on the most practical volumes to expect a facility to handle. The Committee also believes, however, that it is desirable to suggest practical capacities based on the normal desires of drivers under certain conditions.**

On most main rural highways, operating conditions are considered satisfactory for the average driver when the operating speed is 45 to 50 miles per hour during all but a few of the peak volume periods in a year.

With this operating speed, the average speed of all vehicles will be 40 to 45 miles per hour and at any one instant about 70 percent of the drivers will feel some effect of congestion, but they will have an opportunity to pass the slower-moving vehicles without unreasonable inconvenience. In certain sections of the country where drivers rarely experience congested conditions or where most trip lengths are relatively long, and on toll roads or other special high-type rural facilities, drivers might consider a highway unreasonably congested when those who so desire could not average 50 to 55 miles per hour during all but a few of the periods of peak volume in a year.

On urban facilities with uninterrupted flow, an operating speed of 35 to 40 miles per hour, resulting in an average speed for all traffic of 30 to 35 miles per hour, is considered reasonable.

Two-lane Roads

Under ideal roadway and traffic conditions a two-lane road where sight distances are not restrictive will accommodate 900 passenger cars per hour and still permit operating speeds of 45 to 50 miles per hour. The corresponding figure for an operating speed of 50 to 55 miles per hour is 600 passenger cars per hour. Studies have shown that the distribution of traffic by directions on a two-lane road has practically no effect on operating speeds or on the average interference between vehicles and relative congestion which the average driver experiences. **The maximum practical capacity of a rural two-lane road with uninterrupted flow is therefore a total of 900 passenger cars per hour regardless of the distribution of traffic by directions.**

Within urban areas or for access connections between industrial plants and the main highways, where operating speeds of 35 miles per hour are satisfactory, the practical capacity of a two-lane road would be 1,500 passenger cars per hour. At certain locations where operating speeds of 50 to 55 miles per hour are required, the practical capacity of a two-lane road would be 600 passenger cars per hour.

Multilane Roads

A multilane highway will provide the same or comparable operating conditions with 1,000 passenger cars per hour per lane in the direction of the heavier traffic flow as a two-lane highway with no restrictive sight distances operating at a total traffic volume of 900 passenger cars per hour. **The maximum practical capacity of a multilane rural highway with uninterrupted flow is therefore 1,000 passenger cars per lane per hour in the direction of the heavier flow.**

A multilane highway with uninterrupted flow will provide an operating speed of 35 to 40 miles per hour when the traffic volume in the one direction of travel is 1,500 passenger

A badly congested multilane highway. Cars in the second lane are here delayed by a vehicle desiring to make a left turn. Uncontrolled right of access has resulted in the conversion of this section of highway to the equivalent of one continuous intersection.

cars per lane per hour. **The maximum practical capacity of multilane freeways in urban areas, when access and egress facilities are not a factor, is 1,500 passenger cars per lane per hour in the direction of the heavier flow.** At this volume, drivers who so desire can safely maintain an over-all speed of 35 to 40 miles per hour, although the average speed of all vehicles will be 30 to 35 miles per hour. Also, exceptionally high volumes that occur frequently for short periods can be handled without complete congestion. There is also further significance in 1,500 vehicles per lane per hour as the maximum practical capacity of multilane roads in that this is the highest rate at which vehicles, after being once stopped, can pass a point in a single line.

Three-Lane Roads

The place of the three-lane, two-way pavement in the highway system has long been the subject of discussion. Three-lane highways have been constructed to accommodate traffic volumes in excess of those that can be handled efficiently by two-lane highways but that are not sufficiently great to require a four-lane road. They have also been built as stage construction projects in the development of four-lane undivided highways. The belief has been expressed, however, that traffic volumes justifying more than two lanes have by their natural growth soon become sufficient to congest a three-lane width. Furthermore, by the time a third lane can be planned and constructed on an already congested two-lane road, the traffic demand requires most of the increased capacity which the third lane provides, and thus the added lane provides only temporary relief.

With the rather recent universal change in favor of four-lane divided rather than undivided highways, there has been a marked tendency toward the elimination of three-lane road construction by going directly to a four-lane divided highway for traffic volumes in excess of those that can be accommodated by a two-lane road. A three-lane road does not lend itself to the ultimate development of a four-lane divided highway.

Hazard to traffic

There have been wide differences of opinion regarding the hazard to traffic on three-lane highways. From the results of the most comprehensive studies of accident rates of three-lane highways as compared with other types, there has, however, been a general acceptance of the belief that a traffic volume greater than can be accommodated by a two-lane highway justifies the added safety that can be provided by a four-lane divided highway.

From the point of view of driver behavior, the three-lane highway suffers a psychological disadvantage which might well result in an abnormally high accident rate. On a two-lane road, a driver engaged in a passing maneuver must encroach upon the left lane which is definitely provided for traffic in the opposite direction. He does this with full realization that his passing is accomplished only in the face of the superior rights of drivers in the opposing lane. In the case of the three-lane road, particularly with traffic evenly divided in the two directions, there is no clear-cut right-of-way distinction. A vehicle moving in one direction has as much right in the center lane as one moving in the other direction, and passings may involve much greater traffic hazards.

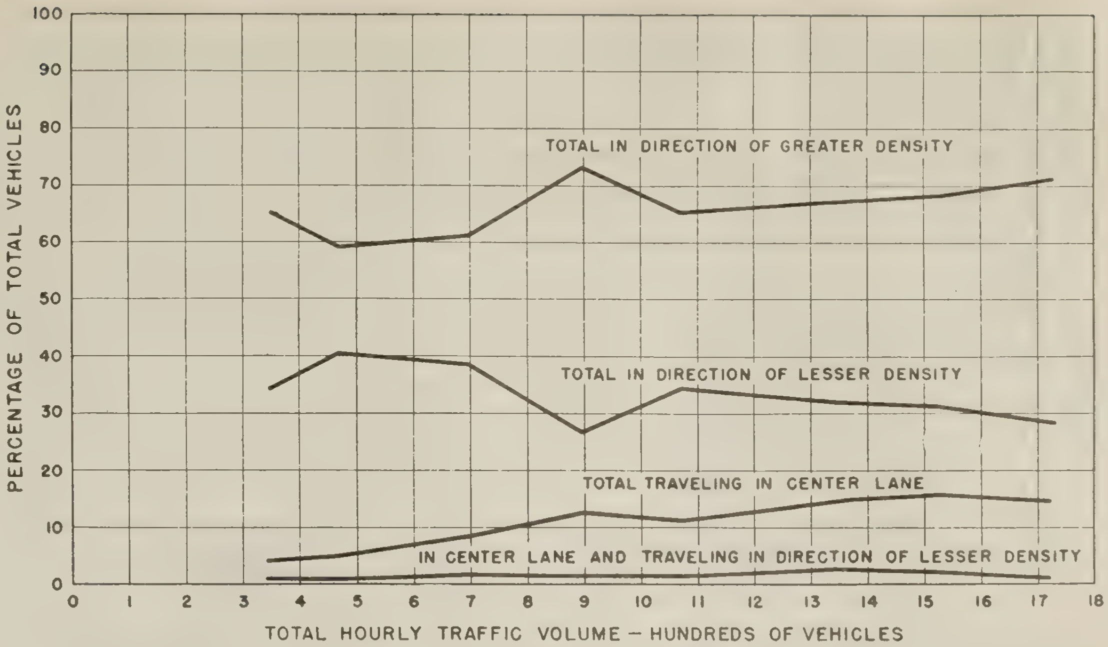


Figure 14.—Distribution of vehicles between lanes on a level, tangent, three-lane highway.

Efficiency

It is commonly assumed that a three-lane highway is more efficient for locations where at least two-thirds of the traffic travels in one direction during high volume periods. This assumption is based on the idea that traffic traveling in the direction of the heavier volume will use two lanes, and traffic in the other direction will use one lane. Based on data obtained on modern three-lane highways with good alinements and profiles, figure 14 shows the percentage of vehicles that use each lane when approximately two-thirds of the traffic is in one direction. The percentage of vehicles traveling in the center lane at any one place increases as the total volume increases to 1,500 vehicles per hour. At this volume, only 15.9 percent of the vehicles were in the center lane, 13.8 percent traveling in one direction and 2.1 percent in the other. One driver had the same right as another to use the center lane of a three-lane highway and, regardless of the opposing traffic volume, he apparently exer-

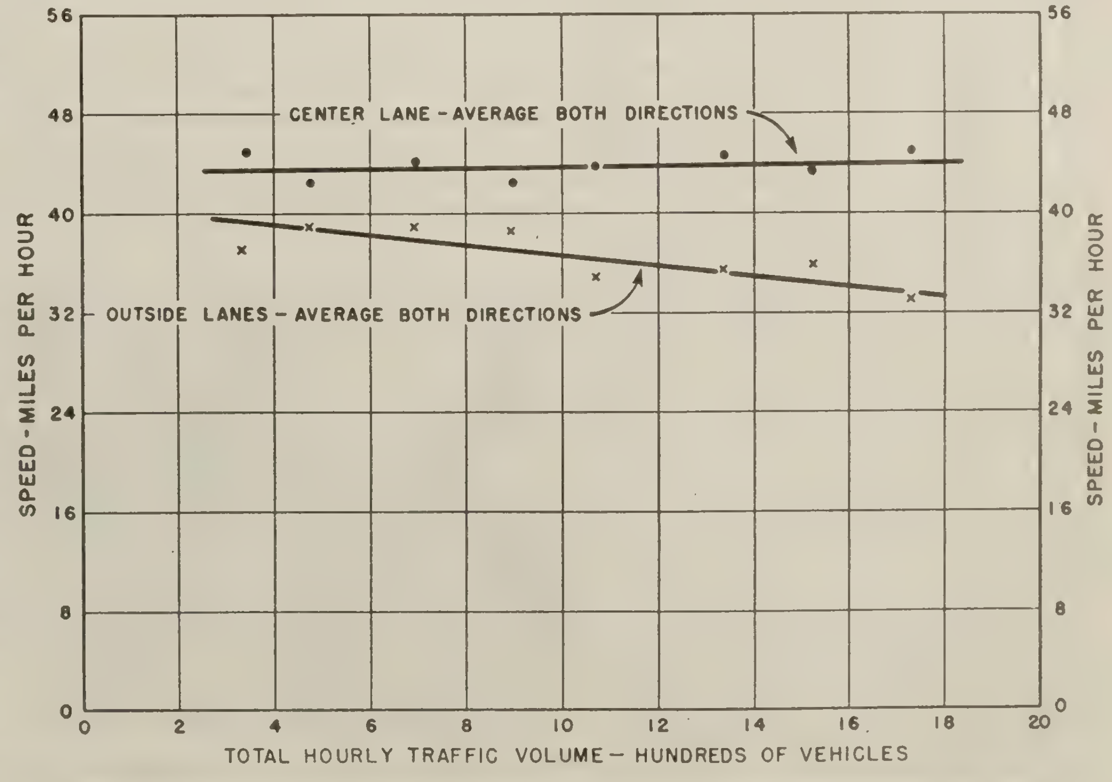


Figure 15.—Vehicle speeds in center and outside lanes on a three-lane highway.

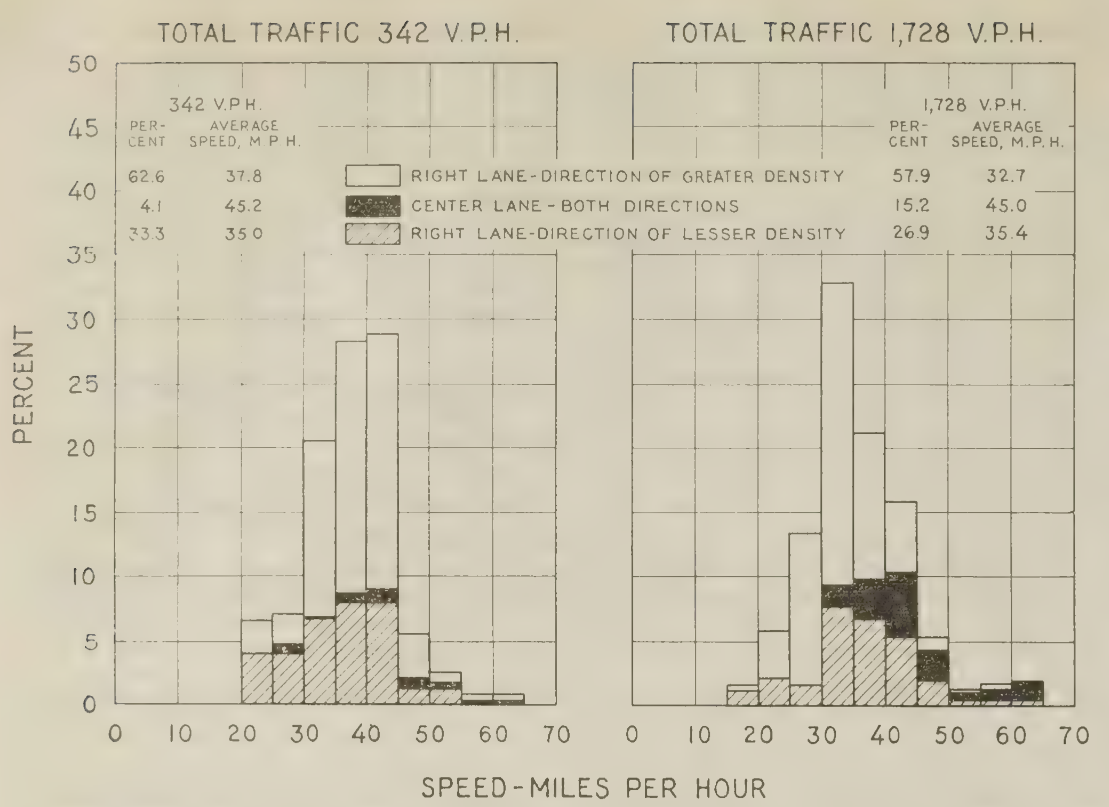


Figure 16.—Frequency distribution of vehicle speeds on a three-lane highway.

cised that right. An estimated maximum of about 300 vehicles per hour, or 15 percent, used the center lane at a volume of 2,000 vehicles per hour, which is well above the practical capacity of a three-lane road.

Figure 15 shows average speeds on three-lane highways for vehicles in the center and outside lanes, at different total volumes. There is a marked decrease in the average speed of vehicles in the right-hand lanes with an increase in the total volume, whereas the average speed for vehicles in the center lane does not change as the volume increases. Figure 16 further illustrates the tendency of drivers to travel at high speeds when using the center lane of a three-lane highway. This figure shows the distribution of speeds by lanes and direction at a low and a high total traffic volume. Although only 15.2 percent of the vehicles were in the center lane at the higher traffic volume, 41.7 percent of those traveling over 40 miles per hour, 58.3 percent of those traveling over 45 miles per hour, and 72.7 percent of those traveling over 50 miles per hour were in the center lane. This tendency of drivers to travel in the center lane of a three-lane highway during heavy traffic volumes at speeds nearly as high as those on four-lane divided highways during low traffic volumes, creates a hazardous condition and contributes to the severity of accidents. On two-lane highways and four-lane divided and undivided highways, drivers tend to reduce their speeds with an increase in the volume of traffic, regardless of the lane they occupy.

A similar analysis for periods when traffic was almost evenly divided by direction showed that under this condition a three-lane highway will handle traffic more efficiently than when the flow is predominantly in the one direction. Apparently the assumption of most efficient operation with two-thirds of the traffic in one direction is a figment of the imagination that cannot be substantiated by facts. Were it true, this assumption could be widely applied because it is the rule, rather than the exception, that about two-thirds of the traffic travels in one direction on any rural highway during periods in which the highest total volumes occur. There are, however, no available data to show that any three-lane highway has ever accommodated more than 2,000 vehicles per hour in one direction; a number that can crowd into a single lane at points where the sight distance is too short for passing maneuvers to be performed safely.

Capacity

With a total of 1,500 passenger cars per hour, a three-lane highway with no restrictive sight distances will provide operating conditions comparable to those on two-lane and four-lane rural highways operating at their practical capacities.

The capacity of three-lane highways is very sensitive to restrictive sight distances.

The maximum practical capacity of a rural three-lane highway is therefore a total of 1,500 passenger cars per hour. This is 67 percent greater than the capacity of a two-lane highway and 75 percent of the capacity of two lanes for one direction of travel on a four-lane highway.

For less favorable sight-distance conditions, the difference between the practical capacities of a two- and a three-lane highway decreases and the difference between the practical capacities of a three- and a four-lane highway increases.

If sight distances sufficient to complete passing maneuvers safely are available only intermittently along a three-lane highway, the practical capacity of such a highway might be only slightly greater than the capacity of a two-lane road with the same alinement; or less than the capacity of a two-lane road with good alinement. **If a three-lane road is to accommodate traffic volumes substantially greater than those that can be accommodated by a good two-lane road, sight distances long enough to permit passing with safety must be almost continuous over the length of the road.**

Experience with three-lane highways

The past experience and practice of State highway departments should offer some index of the place of three-lane roads in our present highway system. Through the Bureau of Public Roads, the Highway Capacity Committee obtained data from the State highway departments showing the date of construction and traffic volumes during the life, or up to the present time, of most three-lane rural roads constructed in this country. Information was obtained from 27 States on more than 3,700 miles of three-lane roads, 7.8 percent of which had been converted to four or more lanes. It must be remembered, when interpreting the results of this study, that a lack of funds and the normal time required to plan, finance, and construct a facility, or other considerations, may have delayed the actual construction of a three-lane road (or the widening of a three-lane road to four lanes) several years after the actual need for the improvement became apparent, and that in some cases the inadequacy of an existing three-lane road was relieved by the construction of an alternate or parallel facility.

The average retirement age of three-lane highways converted to four lanes was 6.1 years, which is 1.6 years less than the average time that existing three-lane roads have been in service. The ages of three-lane roads when converted to four or more lanes varied from 15 years with an initial annual volume of less than 1,000 vehicles per day to less than 2 years for initial annual volumes exceeding 10.000 vehicles per day. The retired three-lane roads carried an average annual traffic volume of 7,029 vehicles per day as compared with an average maximum traffic volume to date of 4,996 vehicles per day for those still in existence. The traffic volumes on three-lane highways as initially constructed, on those still in existence, and on those that have been converted to wider highways, are shown in figure 17.

Prior to widening, 17 percent of the reported three-lane mileage carried annual average volumes of 10,000 and more vehicles per day. Only 5 percent of the existing three-lane mileage has carried annual volumes of 10,000 and more vehicles per day.

California and New Jersey each reported three-lane roads with exceedingly high annual volumes. On only one of these highways, however, has the peak hourly volume exceeded 2,000 vehicles. The following tabulation shows the peak hourly volumes on the three-lane roads in California carrying average annual volumes exceeding 10,000 vehicles per day.

Average daily traffic in year of highest annual volume:	*Peak hourly volume*
11,272	1, 589
12,076	1, 895
13,375	891
12,503	1, 083
12,351	918
19,040	1, 958

It is evident that these three-lane roads were taxed beyond their possible capacities during peak periods, and the peak hourly volumes were much lower than they would have been had the capacities of the roadways been greater.

Conclusions of studies

The more detailed results of the studies made by the Committee regarding three-lane roads may be obtained in mimeograph form from the Highway Research Board. The important conclusions of this study were:

1. At any point on a three-lane highway, relatively few vehicles travel in the center lane. The maximum number that can be in the center lane is about 300 per hour, regardless of the total traffic volume, when up to 70 percent of the total traffic is traveling in one direction.

2. Although there is a very marked drop in the average speed of traffic in the outside lanes with an increase in volume, there is no drop in the speeds of vehicles in the center lane.

3. As long as the hourly traffic volume traveling in one direction does not exceed 70 percent of the total traffic, the center lane will be used by vehicles traveling in both directions.

4. The average speed of all vehicles and the possible capacity of a three-lane road are slightly higher when the traffic is nearly evenly divided by direction than when two-thirds travel in one direction.

5. At places where sight distance is restricted, the use of the center lane for passing is dangerous; so, in effect, a three-lane highway will carry only two lanes of traffic at such points.

6. A three-lane highway having even one restricted sight distance cannot carry more vehicles per hour in one direction than the number that can crowd into one traffic lane—2,000 passenger cars per hour under ideal conditions.

7. Three-lane roads with an initial annual average volume of about 4,700 vehicles per day may be expected to give a useful service for approximately 6 years.

8. Three-lane roads with an initial annual average volume less than 3,300 vehicles per day may be expected to give satisfactory service for at least 13 years, and perhaps for the normal life of the pavement (15–20 years) providing traffic increases in the future at the same rate that it has in the past, excluding the war years.

Table 5.—*Roadway capacities for uninterrupted flows under ideal traffic and roadway conditions*

	Two-lane, two-way highway: total for both lanes [1]	Three-lane, two-way highway: total for all lanes [1]	Multi-lane highway: average per lane for direction of heavier flow [2]
	Passenger cars per hour	*Passenger cars per hour*	*Passenger cars per hour*
Basic capacity [3]	2,000	4,000	2,000
Practical capacity for urban conditions [4]	1,500	2,000	1,500
Practical capacity for rural conditions [5]	900	1,500	1,000

[1] Distribution by directions is not a factor.

[2] During periods of peak flow, traffic in one direction may be much heavier than in the other direction.

[3] Same as possible capacity for ideal conditions.

[4] Provides 35 to 40 m.p.h. operating speeds.

[5] Provides 45 to 50 m.p.h. operating speeds.

EFFECT OF FACTORS THAT REDUCE CAPACITIES

Table 5 summarizes the basic, possible, and practical hourly capacities of various types of highways under ideal traffic and roadway conditions when the flow is uninterrupted and sight distances are not restrictive.

It is seldom, however, that roadway and traffic conditions are ideal. For this reason, both possible and practical capacities for uninterrupted flow are usually lower than those shown in table 5. If surface condition be disregarded, and it is seldom a factor on a well-maintained highway with a high-type surface, the most important conditions which affect the capacity of the highway where the flow is not interrupted by cross traffic are: (1) lane width, (2) clearances to lateral obstructions, (3) shoulder width and condi-

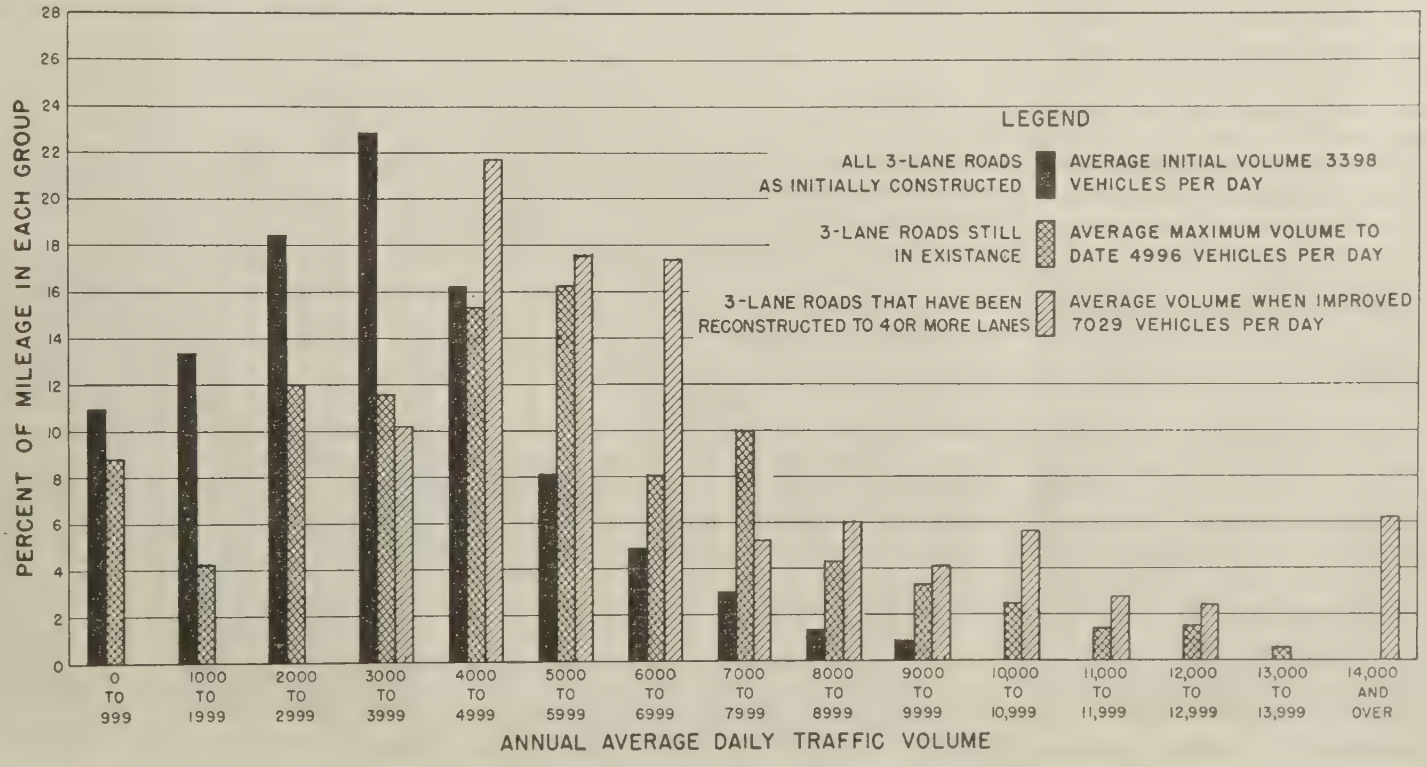


Figure 17.—Past experience with three-lane highways, based on all three-lane construction on State highways (totaling 3,740 miles).

Table 6.—*Effect of lane width on capacity* [1]

Lane width	Capacity expressed as a percentage of 12-foot lane capacity		
	Two-lane rural roads—		Two lanes for one direction of travel on divided highways at practical capacities
	At possible capacities	At practical capacities	
Feet	*Percent*	*Percent*	*Percent*
12	100	100	100
11	88	86	97
10	81	77	91
9	76	70	81

[1] Effects of lane width on driver comfort, accident rates, etc., are not included in these relations.

Table 7.—*Effect of restricted lateral clearance on practical capacities* [1]

Clearance from pavement edge	Effective width of two 12-foot traffic lanes
Feet	*Feet*
6	24
4	23
2	21
0	18

[1] Effects of lateral clearance on driver comfort, accident rates, etc., are not included in these relations.

This underpass offers no impediment to the free movement of traffic. Ample side clearance is assured even if a third lane is later added to the pavement.

Table 8.—*Combined effect of lane width and edge clearances on highway capacities* [1]

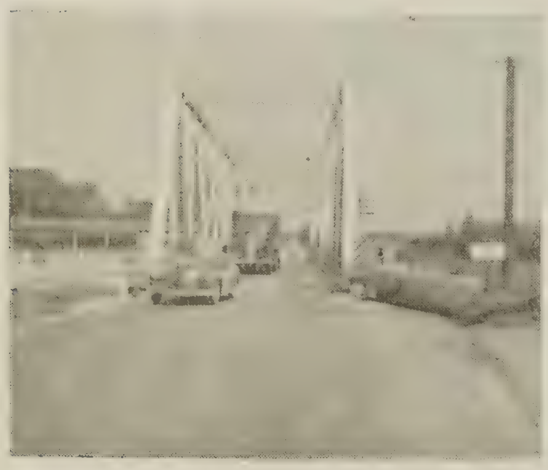
Clearance from pavement edge to obstruction	Capacity expressed as a percentage of the capacity of two 12-foot lanes with no restrictive lateral clearances							
	Obstruction on one side				Obstruction on both sides			
	12-foot lanes	11-foot lanes	10-foot lanes	9-foot lanes	12-foot lanes	11-foot lanes	10-foot lanes	9-foot lanes
POSSIBLE CAPACITY OF TWO-LANE HIGHWAY								
Feet								
6	100	88	81	76	100	88	81	76
4	97	85	79	74	94	83	76	71
2	93	81	75	70	85	75	69	65
0	88	77	71	67	76	67	62	58
PRACTICAL CAPACITY OF TWO-LANE HIGHWAY								
6	100	86	77	70	100	86	77	70
4	96	83	74	68	92	79	71	65
2	91	78	70	64	81	70	63	57
0	85	73	66	60	70	60	54	49
POSSIBLE AND PRACTICAL CAPACITIES OF TWO LANES FOR ONE DIRECTION OF TRAVEL ON DIVIDED HIGHWAYS								
6	100	97	91	81	100	97	91	81
4	99	96	90	80	98	95	89	79
2	97	94	88	79	94	91	86	76
0	90	87	82	73	81	79	74	66

[1] Effects of lane widths and lateral clearances on driver comfort, accident rates, etc., are not included in these relations.

tion, (4) commercial vehicles, (5) location and design of interchange facilities, and (6) the profile and alinement, especially as related to sight distance and gradient.

Lane Width

Narrow lanes have a lower capacity than the 12-foot lanes which are at present considered necessary for heavy volumes of mixed traffic. On a two-lane road, a vehicle performing a passing maneuver must encroach on the lane normally used by traffic traveling in the opposite direction for a longer period if the lanes are narrow than if they are wide. On multilane roads, more vehicles straddle the lane lines when the lanes are narrow than when they are wide, thereby in effect occupying two lanes rather than one. Table 6 shows the capacity of lanes down to 9 feet in width on the basis of capacities for 12-foot lanes. The practical capacity of a two-lane rural road with lanes 9 feet wide, for example, is only 70 percent of the capacity of a similar road with 12-foot lanes.



Narrow through-truss bridges seriously impair the capacity of many sections of highway.

Restrictive Lateral Clearances

Vertical obstructions such as retaining walls, light poles, and parked cars adjacent to the edge of a traffic lane reduce the effective width of that lane as shown by table 7. A 24-foot pavement with a bridge truss at the edge, for example, has the same effective width as an 18-foot pavement with 6-foot shoulders. In addition to their effect on capacity, lane width and lateral clearances also affect driving comfort, accident rates, etc., which the relationships shown by these tables do not include.

The combined effect on capacity of lane width and clearances from the pavement edge to obstruction are shown by table 8. Some judgment must obviously be exercised when applying these adjustments to highway sections where the lateral restrictions are not continuous along the entire length. One lateral restriction within a section of highway will cause a bottleneck and thereby directly affect the *possible* capacity of the entire sec-

Narrow shoulders, and shoulders that are poorly maintained, seriously impair the capacity of a highway.

A short-span bridge of inadequate roadway width.

tion. The *practical* capacity of the section, however, may be affected only slightly.

For example, one bridge 24 feet wide and 100 feet long on a highway with a 24-foot surface and a normal shoulder width of 8 feet would reduce the *possible* capacity of that entire section by 24 percent (from 100 to 76 percent, table 8). The *practical* capacity, however, would be influenced for only a short distance, thereby affecting the practical capacity of the entire section a lesser amount, in proportion to the relative lengths.

While no research data are available regarding the exact length of highway over which an individual obstruction within 6 feet of the pavement edge affects traffic operations, it seems reasonable, from the results of observations for other purposes, to assume that traffic will be affected to some extent for 9 seconds before reaching the lateral obstruction and that the net effect will be approximately the same as the full effect while traveling for 4½ seconds plus the distance over which the restrictive clearance continued. With traffic averaging 45 miles per hour the bridge in the above example would affect traffic over a distance of 397 feet (297+100). The practical capacity of the entire section of highway, if it were 1 mile long, would then be reduced by the narrow bridge from 100 percent, the practical capacity of a highway with 12-foot lanes and no lateral restrictions, to

$$\frac{(100\times 4{,}883)+(70\times 397)}{5{,}280}=93 \text{ percent of the}$$

capacity of a highway with 12-foot lanes and no lateral restrictions.

Table 8 shows the combined effect of lane width and lateral clearances for two-lane highways and for divided four-lane highways. For undivided four-lane highways, the lateral clearance on the left side of the lanes for travel in the one direction may be assumed to be equivalent to the distance from the left edge of these lanes to a vehicle centered in the adjacent lane used by traffic traveling in the opposite direction.

Likewise, when there are more than two lanes for the one direction of travel, interior lanes may be assumed to have the same capacity as lanes with lateral clearances equivalent to the distance between the edge of the lane and a vehicle centered in the adjacent lane. For example, if conditions are such that the practical capacity for one direction of travel on a four-lane divided highway with a wide median, 10-foot shoulders, and 12-foot lanes is 1,500 passenger cars per lane per hour, then, for similar conditions the practical capacity of the three 10-foot lanes for one direction of travel on a six-lane divided highway with a wide median and 10-foot shoulders would be:

For lanes 1 and 3 [3]__ 0.91×1,500×2=2,730
For lane 2 [4]________ 0.86×1,500 =1,290
Total_______________________ 4,020

Shoulders

At no time are adequate shoulders more necessary on a highway than when the lanes are used to full capacity. Without a place of refuge outside the traffic lanes, one disabled vehicle can reduce the capacity of a highway by more than the capacity of one lane, especially if the lanes are less than 12 feet wide. The disabled vehicle blocks the lane occupied and, in addition, reduces the capacity of adjoining lanes whenever vehicles must merge into fewer lanes at speeds below 30 miles per hour. For example, the possible capacity of a traffic lane with vehicles moving at 20 miles per hour is only 87 percent of its capacity at 30 miles per hour. At 10 miles per hour a lane has only about 50 percent of its 30-mile-per-hour capacity (see fig. 3). A minor accident which causes a reduction in speed can, therefore, cause complete congestion on a facility operating near its possible capacity. For lanes less than 12 feet wide, shoulders treated with bituminous materials for a width of 4 feet or more increase the effective width of the adjacent traffic lanes by 1 foot.

Consideration must be given to the needs of disabled vehicles, of which one may be expected for every eight to ten thousand vehicle-miles of travel, if all traffic is to be properly served.

Bridge rails must be well removed from the edge of the pavement if they are to have no effect on the traffic capacity of a highway.

Commercial Vehicles

Commercial vehicles reduce both the practical and possible capacities of a highway (see table 9) in terms of vehicles per hour because they occupy a greater road space and influence traffic over a larger area than do passenger cars. They also generally travel at lower speeds, especially on upgrades, thereby increasing the number of passing maneuvers that are necessary for other vehicles to maintain reasonable speeds. On multilane facilities with uninterrupted flow, one commercial vehicle (includes only those vehicles having

Table 9.—*Effect of commercial vehicles on practical capacities of multilane facilities*

Commercial vehicles	Capacity expressed as a percentage of passenger-car capacity on level terrain	
	Level terrain	Rolling terrain
Percent	*Percent*	*Percent*
None	100	100
10	91	77
20	83	63

---

[3] Factor of 0.91 from table 8, 10-foot lanes with no obstructions.

[4] Factor of 0.86 from table 8, 10-foot lane with clearances of 2 feet on either side to cars in adjoining lanes.

The effect of trucks on capacity is greatest where alinement is poor and grades are long and steep.

dual tires on rear axle) has approximately the effect of two passenger cars in level terrain, and of four passenger cars in rolling terrain.

For example, approximately the same operating conditions will prevail on an expressway through rolling terrain when there are 1,500 passenger cars per lane per hour as when there are 115 trucks and 1,040 passenger cars per lane, a total of 1,155 vehicles.

In mountainous terrain the effect varies widely with the particular profile but, as an average, one commercial vehicle has approximately the same effect as eight passenger cars. The values of table 9 apply only to percentages of commercial vehicles within normal limits and do not include the effect of bus stops, etc. Care must be exercised in their application because the percentage of commercial vehicles during peak hours is generally considerably lower than the average percentage during all hours. On two-lane highways, the effect of commercial vehicles is about 25 percent greater than on multilane expressways.

Imperfect Alinement

The alinement and profile of a highway are important factors affecting its capacity at different operating speeds. In combination, they influence the sight distances along the highway or the length of roadway visible to the driver at any point on the roadway when the view is unobstructed by other traffic. To determine operating conditions on a highway, sight distance is divided into two categories: stopping sight distance and passing sight distance.

Table 10.—*Percentage of total traffic and percentage of passed vehicles traveling at various speeds on two-lane highways where sight distances and oncoming traffic do not restrict passing opportunities*

Speed group (m. p. h.)	Average main rural highway		Highest-speed rural highways	
	All traffic	Passed vehicles	All traffic	Passed vehicles
	Percent	*Percent*	*Percent*	*Percent*
Over 50	11	1	39	5
40 to 49	57	15	43	40
30 to 39	30	54	17	40
Below 30	2	30	1	15
Total	100	100	100	100

Stopping sight distance is the distance required by the driver of a vehicle, traveling at a given speed, to bring his vehicle to a stop after an object on the roadway becomes visible. Passing sight distance is the minimum sight distance that must be available to enable the driver of one vehicle to pass another vehicle safely and comfortably, without interfering with the speed of an oncoming vehicle should it come into view after the overtaking maneuver is started. Stopping sight distances are necessary continuously on all types of highways, whereas passing sight distances are necessary only on two-way roadways with two or three lanes.

Heavy grades, as a rule, have little effect on the speeds of passenger cars. It is the restrictive sight distances, which usually accompany steep grades, that create congestion at low volumes in mountainous terrain.

Where sight distances are inadequate on two- and three-lane highways, drivers are restricted in much the same manner as if the lane used for passing were filled with oncoming vehicles. The prudent driver must always assume the existence of an approaching vehicle just beyond the limit of his sight distance. The reduction in capacity caused by short sight distances can be obtained by using as a criterion the percentage of the total highway on which sight distances are insufficient to permit passing maneuvers to be performed safely.

The results of passing-practice studies conducted by the Bureau of Public Roads in cooperation with several State highway departments at locations where the alinement and profile provided unlimited opportunities for passing reflect the need for passing sight distances on two-lane rural highways. Table 10 shows the speed of the vehicles that were passed related to the speeds of all vehicles on the average main rural highway and on the highest-speed rural highways during periods of low traffic when passings could be made almost without interference from oncoming traffic.

Table 11.—*Effect of passing sight-distance restriction on practical capacities of two-lane highways when adequate stopping sight distances are always present* [1]

Percentage of total length of highway on which sight distance is restricted to less than 1,500 feet	Practical capacity, in passenger cars per hour—	
	For operating speed [2] of 45–50 miles per hour	For operating speed [2] of 50–55 miles per hour
0	900	600
20	860	560
40	800	500
60	720	420
80	620	300
100	500	160

[1] The data in this table apply to sections with 12-foot traffic lanes, shoulders adequate for parking disabled vehicles clear of the traffic lanes, and a continuous stopping sight distance corresponding to the design speed Also, the sight distance on the restricted portions of the section must be uniformly distributed between the required stopping sight distance for the design speed and 1,500 feet.

[2] Average speed for drivers trying to travel at maximum safe speed.

Since these are the conditions that exist where alinement provides unlimited opportunities for passing, the greatest need on rura two-lane highways is for sight distances that will permit vehicles traveling under 50 miles per hour to be passed safely.

The results of the passing-practice studies show that for the most critical condition, when the passing vehicle first slows to the speed o the passed vehicle before accelerating to perform the passing maneuver, a sight distance to the road surface of 1,500 to 2,000 feet is required to pass a vehicle traveling between 45 and 50 miles per hour with the possibility of oncoming traffic traveling 70 miles per hour

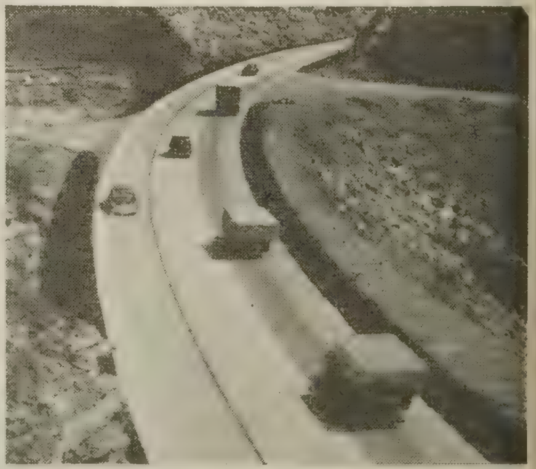


Photo by Portland Cement Association

In mountainous terrain the effect of truck on highway capacity can be minimized by the construction of added lanes on up grades. This is not a three-lane road in the usual sense.

Passing sight distances within the range of 1,500 to 2,000 feet are, therefore, those most widely needed at frequent intervals on rural highways.

Where sight distances within the range of 1,500 to 2,000 feet are not continuously available throughout the length of a two-lane highway, the percentage of the total length of highway with a 1,500-foot sight distance can be used as a criterion of the highway's practical capacity. Table 11 shows the reduction in capacity caused by sight-distance restrictions when operating speeds of 45 to 50 and of 50 to 55 miles per hour are desired.

Figure 18 shows in more detail the effect of passing sight-distance restrictions on the capacity of two-lane highways for various operating speeds.

Grades

Grades affect the capacity of a highway in three ways, as follows:

1. Vehicle braking distance is less on upgrades and greater on down grades than on the level, thereby permitting shorter spacings between vehicles that are climbing grades, and requiring longer spacings between vehicles going down grades, in order to maintain a safe headway.
2. The presence of a grade generally causes a restriction in the sight distance, thereby affecting the percentage of highway on which passing maneuvers can be performed safely.
3. Commercial vehicles with their normal loads travel at slower speeds up grades than on the level, especially if the grade is long and steep. This is also true to some extent for passenger cars. Most passenger cars, however, can negotiate long 6- and 7-percent grades at speeds above 30 miles per hour. The effect that grades up to 7 percent have on capacity as related to the performance of passenger cars is therefore generally negligible.

In the discussion of commercial vehicles, it was stated that one commercial vehicle on a multilane highway has approximately the same effect on capacity as two passenger cars in level terrain and as four passenger cars in rolling terrain. It was also stated that their effect on capacity for two-lane highways is 25 percent greater than on multilane highways. The figures refer to general conditions over the entire length of a highway. In considering the effect of an individual grade, the length and rate of grade are important factors.

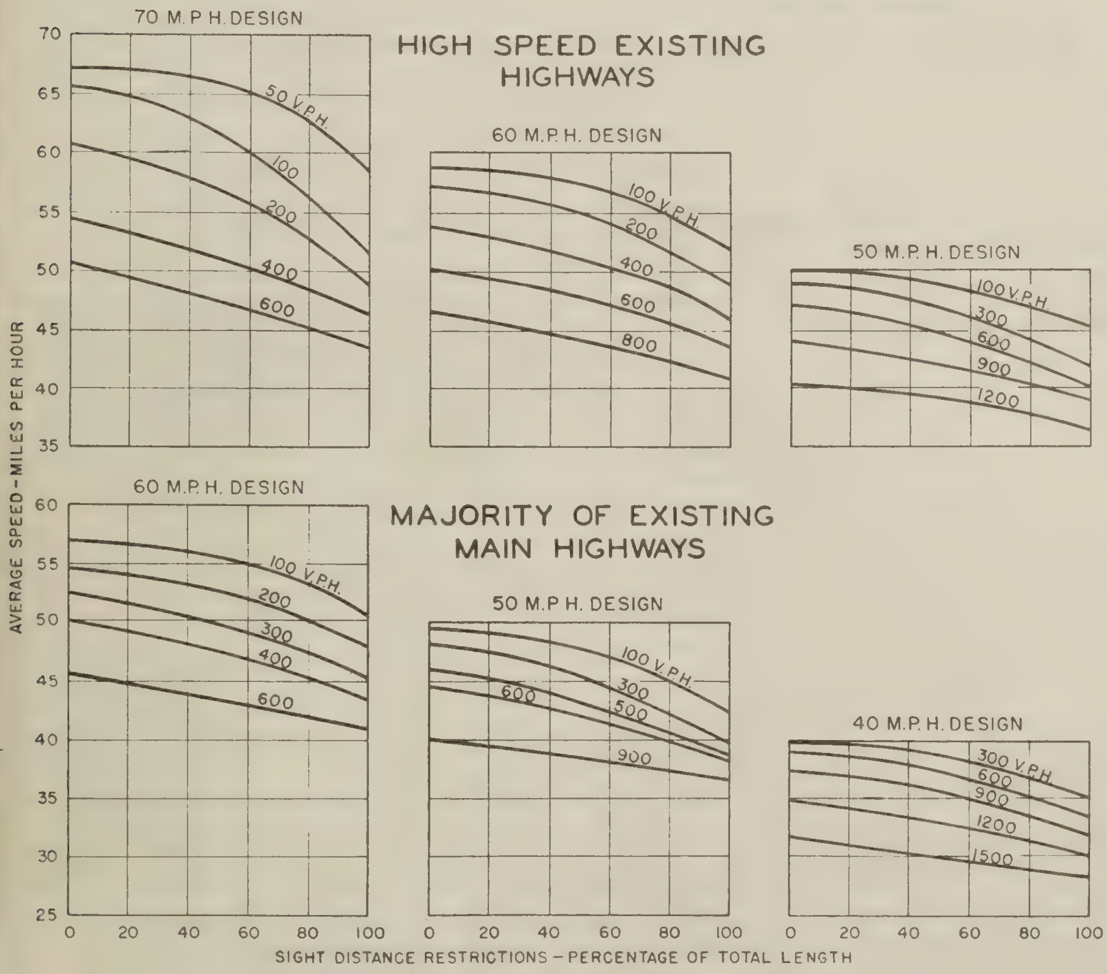


Figure 18.—Possible average speed at different traffic volumes, for drivers trying to travel at the design speed, when the sight distances on various portions of the highway are less than the passing sight distance.

Table 12.—*Distance from bottom of grade at which speed of trucks is reduced to 30 miles per hour* [1]

Grade	Distance from bottom of grade	Vertical climb from bottom of grade
LIGHT-POWERED TRUCKS WITH GROSS LOADS OF 30,000 POUNDS		
Percent	*Feet*	*Feet*
2	2,000	40
3	1,090	33
4	760	30
5	570	29
6	470	28
7	400	28
8	325	26
MEDIUM-POWERED TRUCKS WITH GROSS LOADS OF 40,000 POUNDS		
2	1,780	36
3	1,035	31
4	740	30
5	550	28
6	450	27
7	390	27
8	320	26

[1] Assuming an approach speed of 40 m.p.h. Bad alinement, weak or narrow bridges, or other hazardous conditions at the bottom of the hill would make this approach speed unsafe.

The relationships between speed of trucks at the bottom of a hill, percentage of grade, and distance upgrade are shown in figure 19 for light-powered motortrucks or combination units and in figure 20 for medium-powered motortrucks or combination units in operation in 1941.

The light-powered vehicles had engines which, on an average, would develop 93 brake horsepower; the medium-powered vehicles had engines which, on an average, would develop 106 brake horsepower. Heavy-powered vehicles in operation in 1941 had engines which would develop, on an average, 115 brake horsepower. At the present time, light-powered vehicles will develop nearly the same brake horsepower as those considered medium-powered in 1941.

From these data, for the power and gross weights of vehicles represented, it is possible to determine how far a vehicle, starting its climb from any speed between 9 and 41 miles per hour, can travel up various grades or combinations of grades before the maximum sustained speed reaches any stated value. The solid curves in figures 19 and 20 indicate the performance that may be expected when the beginning speed is above the possible sustained or crawl speed. The broken lines, starting at 9 miles per hour, show what performance may be expected when the hill is approached at crawl speed.

Table 12, for example, shows the distance that light-powered trucks with gross loads of 30,000 pounds, and medium-powered trucks with gross loads of 40,000 pounds, can go up various grades before their speeds are lowered to 30 miles per hour, assuming that they enter the grade at 40 miles per hour. It will be noted that the length of grade that reduces the speed to 30 miles per hour is approximately the same for the light-powered trucks with gross loads of 30,000 pounds as for the

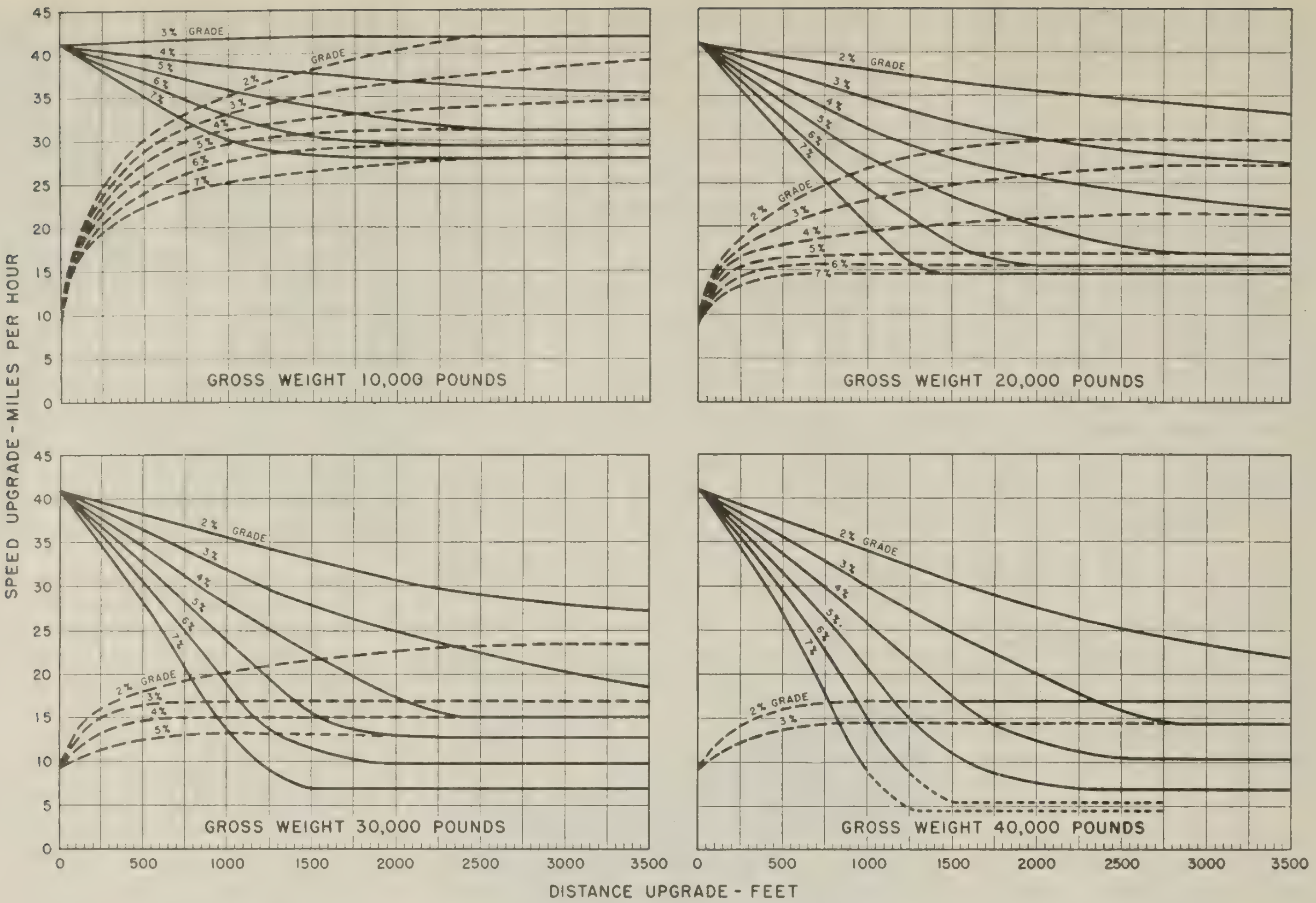


Figure 19.—Effect of length of grade on the speed of light-powered trucks and combinations.

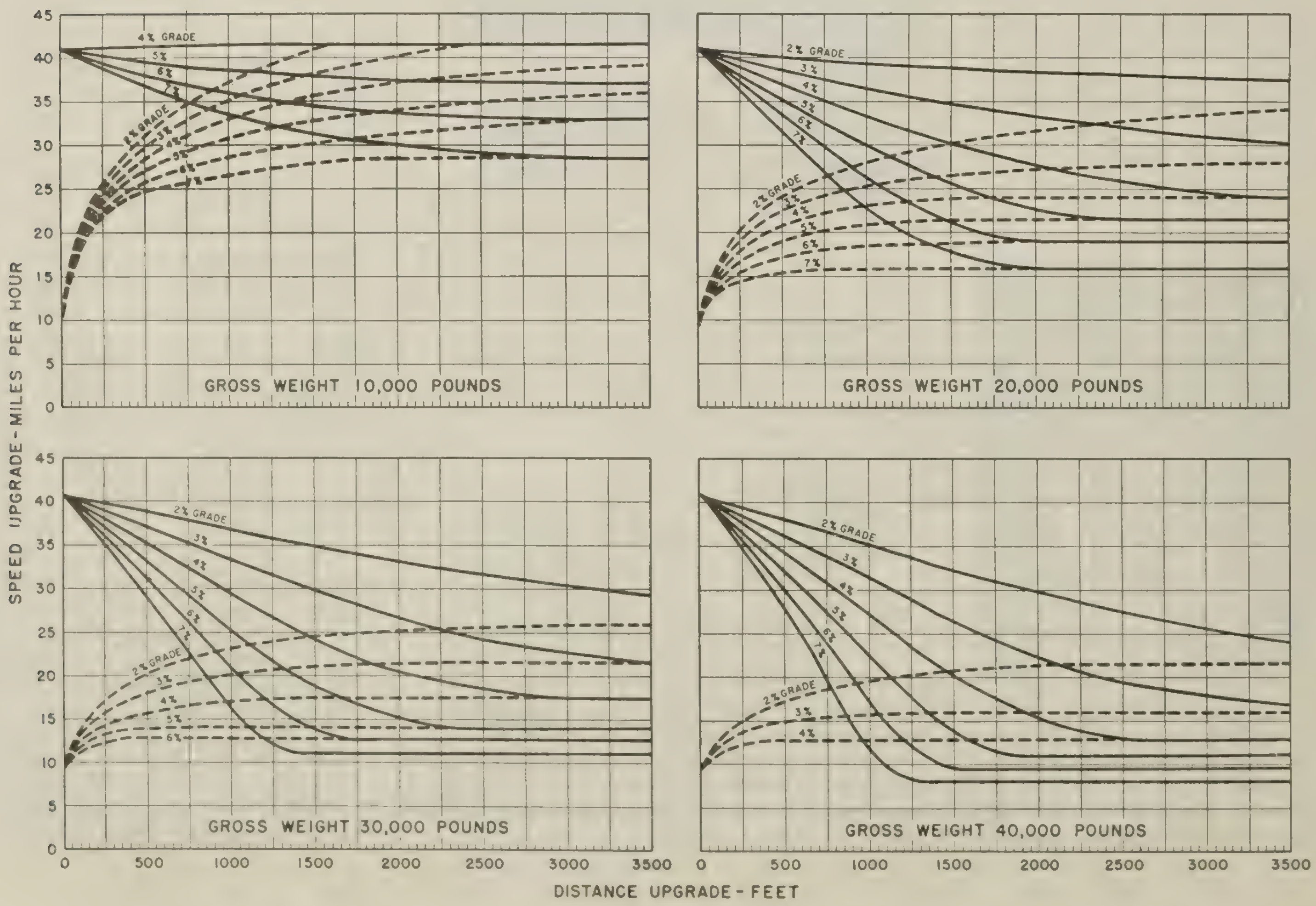


Figure 20.—Effect of length of grade on the speed of medium-powered trucks and combinations.

Table 13.—*Effect of commercial vehicles and grades on the capacity of two-lane highways with uninterrupted traffic flow when the grade does not cause a restriction in the passing sight distance*

Length of grade	Equivalent of one dual-tired commercial vehicle, in terms of passenger cars, on a grade averaging—				
	3 percent	4 percent	5 percent	6 percent	7 percent
Miles					
0.1	3.9	4.1	4.2	4.2	4.4
0.2	4.1	4.3	4.5	4.7	5.1
0.4	4.3	4.6	4.9	5.3	5.5
0.6	4.4	4.8	5.2	5.8	6.5
0.8	4.6	5.1	5.7	6.4	7.1
1.0	4.6	5.3	6.0	6.7	7.4
1.5	4.8	5.6	6.3	7.0	7.7
2.0	5.0	5.8	6.5	7.2	8.0
3.0	5.0	6.0	6.6	7.3	8.2
4.0	5.1	6.0	6.7	7.4	8.3
5.0	5.1	6.0	6.7	7.6	8.3
6.0	5.1	6.0	6.8	7.6	8.3

medium-powered trucks with gross loads of 40,000 pounds. Grades longer than those shown in table 12 would, therefore, have an effect on the possible capacity of a highway because they reduce the speed of trucks that occur with considerable frequency to speeds below 30 miles per hour, the optimum speed for maximum capacity.

If, for the time being, we disregard the effect that grades have in causing sight-distance restrictions, the effect of one commercial vehicle on highway capacity, in terms of passenger cars, is as shown in table 13. There would obviously be an additional effect due to the restrictive sight distances on the grade which would prevent passing maneuvers from being performed as readily as on a level section. The effect due to restrictive sight distances, as shown in table 11, must therefore be added to the effect shown in table 13. To illustrate the total effect that one commercial vehicle has on capacity in terms of passenger cars, including the effect of imperfect alinement, table 14 has been prepared assuming that the percentage of restrictive sight distance increases from 30 percent for a 3-percent grade to 70 percent on a 7-percent grade. For specific conditions, these percentages should be modified to correspond with actual conditions.

Table 14.—*Effect of commercial vehicles and grades on the capacity of two-lane highways with uninterrupted traffic flow, with passing sight distance restricted for 1,500 feet ahead of the crest and a typical alinement elsewhere along the grade*

	Equivalent of one dual-tired commercial vehicle, in terms of passenger cars, on a grade averaging—				
	3 percent	4 percent	5 percent	6 percent	7 percent
Percentage of highway with restricted sight distance (assumed as typical)	30	40	50	60	70
Capacity of highway with restricted sight distance, as a percentage of unrestricted capacity	87	81	75	69	62
Length of grade, in miles:					
0.1	5.8	7.1	8.6	10.2	12.5
0.2	6.0	7.4	9.0	10.9	13.6
0.4	6.3	7.8	9.6	11.6	14.6
0.6	6.5	8.2	10.1	12.5	16.1
0.8	6.6	8.5	10.6	13.0	16.8
1.0	6.7	8.7	11.0	13.5	17.4
1.5	6.9	9.0	11.5	14.1	18.2
2.0	7.0	9.3	11.9	14.5	18.4
3.0	7.1	9.4	12.0	14.7	19.0
4.0	7.1	9.4	12.1	14.7	19.1
5.0	7.2	9.5	12.1	14.8	19.1
6.0	7.3	9.6	12.1	14.9	19.1

The data shown in table 14 can be applied to a number of problems: For example, table 15 shows the relation of length and rate of grade and of traffic volume to the type of facility required in order to provide operating conditions equivalent to conditions on a level stretch with 800 vehicles per hour, including 10 percent commercial vehicles.

Table 15.—*Effect of grades on type of highway facility required when the traffic includes 10 percent commercial vehicles with dual rear tires*

Gradient	Traffic volume	Length of grade	Type of facility required to provide satisfactory operating conditions for passenger cars [1] [2]		
			Two-lane highway	Two-lane highway with truck lane on uphill side	Four-lane highway
Percent	*Vehicles per hour*				
0	800 or less	Any length	×	--	--
	Over 800 [3]	Any length	----	--	×
3	550 or less	Any length	×	--	--
	551 to 800	1,100 feet or less	×	--	--
		Over 1,100 feet	--	×	--
	Over 800 [3]	Any length	--	--	×
4	500 or less	Any length	×	--	--
	501 to 800	800 feet or less	×	--	--
		Over 800 feet	--	×	--
	Over 800 [3]	Any length	--	--	×
5	400 or less	Any length	×	--	--
	401 to 800	600 feet or less	×	--	--
		Over 600 feet	--	×	--
	Over 800 [3]	Any length	--	--	×
6	350 or less	Any length	×	--	--
	351 to 400	4,000 feet or less	×	--	--
		Over 4,000 feet	--	×	--
	401 to 800	Under 500 feet	×	----	--
		500 to 4,000 feet	--	×	--
		Over 4,000 feet	--	--	×
	Over 800 [3]	Any length	--	--	×
7	300 or less	Any length	×	--	--
	301 to 350	4,000 feet or less	×	--	--
		Over 4,000 feet	--	×	--
	351 to 800	Under 500 feet	×	--	--
		500 to 4,000 feet	--	×	--
		Over 4,000 feet	--	--	×
	Over 800 [3]	Any length	--	--	×

[1] Satisfactory operating conditions for passenger cars are here considered as the equivalent of a capacity of 800 vehicles per hour on level sections of a two-lane highway.

[2] This table is based on the assumptions that a three-lane highway on which traffic in both directions has an equal right in the center lane has no place in modern highway design. Also, when the hourly traffic volume used for design purposes (30th highest hourly volume in the year) exceeds 800 vehicles, a four-lane divided highway is required for any condition of gradient or alinement. If the sight distance is restricted to less than 1,500 feet on portions of the highway other than the grade under consideration, an added truck lane or a four-lane highway may be needed for traffic volumes lower than those shown in the table.

[3] If volume is sufficiently high, a truck lane may be necessary on the uphill side of a four-lane highway, or a multilane highway of more than four lanes may be required.

CAPACITIES EXPRESSED AS AVERAGE ANNUAL DAILY TRAFFIC VOLUMES

The relation between peak hourly rates of flow and annual average daily traffic volumes is the subject of part VIII of this report. There, a method is outlined for converting peak hourly volumes into average daily volumes. It is shown that if the average daily traffic is known, the hourly volume during peak periods can be estimated by applying certain known factors. Conversely, the hourly capacity for a highway may be converted to an average annual daily volume by applying the reciprocal of the factor. For most rural highways the factor for this purpose is between 15 and 16 percent, with a typical value of 15.6 percent. Thus, for a two-lane rural highway with ideal conditions, the average daily volume which will correspond to the practical capacity of 900 vehicles per hour is 900÷0.156=5,750 vehicles per day. This is an average value and consequently will differ according to locality. As a matter of interest, table 16 has been prepared for the purpose of showing average annual daily traffic volumes corresponding to the practical capacities of various types of highways, using the factor 15.6 percent.

It should be obvious that volumes of the magnitude shown in this table are seldom achieved without exceeding the practical capacity, because the high design standards upon which they are based can be economically justified in rare cases only. Particularly is this true for two-lane roads, the capacities of which are very sensitive to restrictive sight distances.

In rolling terrain the alinement may be such as to cause a reduction of 50 percent or more in the average daily volumes for two-lane roads as shown in table 16. For any specific highway, an evaluation of the several factors affecting capacity must precede the computation of a reasonable value for the annual average daily traffic volume.

Table 16.—*Average annual daily traffic volumes corresponding to the practical capacities of different types of highways, as based on the Nation-wide average relationship between the thirtieth highest hourly volume and the average annual daily traffic volume* [1]

Type of traffic		Average annual daily traffic volume on—					
		Two-lane rural roads		Four-lane rural roads [2]		Four-lane urban expressways [2]	
Percentage of passenger cars	Percentage of commercial vehicles	In level terrain	In rolling terrain	In level terrain	In rolling terrain	In level terrain	In rolling terrain
100	0	5,750	5,750	19,250	19,250	37,500	37,500
90	10	5,200	4,450	17,500	14,800	34,000	29,000
80	20	4,800	3,600	16,050	12,000	31,000	23,500

[1] Except for the presence of commercial vehicles, roadway and traffic conditions are assumed to approach the ideal, including 12-foot traffic lanes, tangent alinement, and uninterrupted flow.

[2] Assuming two-thirds of traffic in heavier direction during peak hour.

APPLICATION OF CAPACITY INFORMATION TO SPECIFIC PROBLEMS

The following examples illustrate correct applications of the data contained in this chapter to specific conditions. In each example the problem is stated first, and the solution is then worked out in three successive steps: First, the capacity under ideal conditions is determined; next, the adjustment factors for existing conditions are obtained from the tables; and finally, these factors are applied to the ideal-condition capacities.

Example 1

Problem

What is the possible capacity of one tube of the Holland Tunnel during periods when 10 percent of the traffic is heavy commercial vehicles? The tube has a 20-foot roadway between curbs, a 1-foot clearance to the vertical walls on each side, and a 4-percent grade.

Solution

For ideal conditions: possible capacity = 2 × 2,000 = 4,000 passenger cars per hour.

Adjustments:

	Factor
Surface width and lateral clearances [5]	0. 80
Commercial vehicles [6]	. 77
Combined factor	0. 616

Application of factor: possible capacity = 4,000 × 0.616 = 2,464 vehicles per hour.

---

[5] Factor obtained from table 8.

[6] Factor obtained from table 9.

Example 2

Problem

What are the possible and practical hourly capacities of a two-lane rural highway with a 20-foot surface and with frequent obstructions within 4 feet of both pavement edges, located in rolling terrain where 10 percent of the peak-hour traffic is commercial vehicles and the sight distance is restricted to less than 1,500 feet over 60 percent of its length?

Solution

For ideal conditions:

Possible capacity = 2,000 passenger cars per hour.

Practical capacity = 900 passenger cars per hour to provide operating speed of 45 to 50 m.p.h.

Adjustments:	*Possible capacity factor*	*Practical capacity factor*
Surface width and lateral clearance [7]	0. 76	0. 71
Commercial vehicles [8]	. 67	. 67
Alinement [9]	1. 00	. 80
Combined factor (product of individual factors)	0. 509	0. 381

Application of factors:

Possible capacity = 2,000 × 0.509 = 1,018 vehicles per hour.

Practical capacity = 900 × 0.381 = 343 vehicles per hour.

---

[7] Factors obtained from table 8.

[8] Factors obtained from table 9, further corrected for increased effect of commercial vehicles on two-lane roads.

[9] Factors obtained from table 11 (practical capacity factor = 720 ÷ 900).

Example 3

Problem

What are the possible and practical capacities of the upper roadway of the San Francisco-Oakland Bay Bridge, which carries passenger cars only, and has three lanes each 9.5 feet wide for traffic traveling in each direction? The roadway is not divided and has high vertical curbs.

Solution

For ideal conditions:

Possible capacity = 2,000 passenger cars per lane.

Practical capacity for operating speed of 35 to 40 m. p. h. = 1,500 passenger cars per lane.

Adjustments (necessary only for the lane widths and lateral clearances):

	Clearance in feet		
	Right	*Left*	*Factor* [10]
Lane 1	0	1. 5	0. 74
Lane 2	1. 5	1. 5	. 78
Lane 3	1. 5	1. 5	. 78

Application of factors:	*Possible capacity*	*Practical capacity*
Lane 1	1, 480	1, 110
Lane 2	1, 560	1, 170
Lane 3	1, 560	1, 170
Total, vehicles per hour	4, 600	3, 450

---

[10] To obtain factor for lane 1, interpolate in table 8 for an average factor between values of zero feet on both sides and clearance of 1½ feet on both sides. Then interpolate between these average factors for 9- and 10-foot lanes.

Estimated Motor-Vehicle Registrations, 1949

Motor-vehicle registrations and the volume of highway travel in the United States continued their upward climb through the first half of 1949 and will surpass last year's record levels before the end of the year, according to preliminary estimates prepared by the Bureau of Public Roads.

Registration reports from State authorities for the first 6 months of 1949 indicate that approximately 43,298,000 private and commercial motor vehicles will be registered during the calendar year, an increase over 1948 registrations of 2,230,000 automobiles, or 6.7 percent, and 446,000 trucks and busses, or 6.1 percent. A tabulation of the estimates, by class of vehicle and by State, appears on the following page.

These estimates do not include vehicles owned by the Federal, State, county, and municipal governments. The number of publicly owned motor vehicles registered in 1948 was 529,062.

The estimated number of automobiles, busses, and trucks that will be registered in 1949 represents a 10-year growth in the motor-vehicle population of 41.4 percent, compared with 15.5 percent for the previous decade of 1930 through 1939. The greatest increase has occurred in trucks and busses, which have risen 74.4 percent over 1939 and 126.8 percent over 1929, while automobiles have increased 35.8 percent since 1939 and 53.9 since 1929.

It now appears, however, that 1949 will be the first year since 1941 in which the percentage increase over the previous year's registrations will be greater for automobiles than for trucks and busses. This is largely the result of the fact that the production of trucks increased more rapidly than that of passenger cars during the immediate postwar years. In 1949 it is expected that automobile production will be the greatest in history, but truck production will be less than for 1948.

The greater increase in automobile registrations resulted, of course, in a slight decrease in the proportion of trucks and busses to the total number of vehicles registered. Contrary to the long-term trend in which trucks and busses have risen from 13.0 percent of total registrations in 1929 to 14.6 percent in 1939 and 18.1 in 1948, they declined slightly to 18.0 percent in 1949.

The relative increases in motor-vehicle registrations during the last two decades have been accompanied by even greater increases in the consumption of motor fuel. With a tentatively estimated 31,400,000,000 gallons to be consumed on the highways by private and commercial motor vehicles in 1949, the increase from 1939 is 52.1 percent and from 1929 is 122.1 percent. The 1949 estimate represents a gain of 5.0 percent over 1948, compared with an increase in 1948 of 7.9 percent over 1947.

The increases in the number of vehicles registered and motor fuel consumed are reflected in the most recent data on rural traffic volumes. It is estimated that there were 2,167,200,000 miles of travel on rural roads in July, the latest month for which figures are available. This is an increase of 7.5 percent over the volume of travel on rural roads in July of last year, and is 25.2 percent more than the volume reported for July 1941.

UNITED STATES DEPARTMENT OF COMMERCE
BUREAU OF PUBLIC ROADS

PRELIMINARY ESTIMATE OF 1949 MOTOR-VEHICLE REGISTRATIONS 1/

(DOES NOT INCLUDE PUBLICLY-OWNED VEHICLES)

AUGUST 1949

STATE	AUTOMOBILES			TRUCKS AND BUSSES			TOTAL		
	REGISTERED 1948 2/	ESTIMATED 1949	PERCENT INCREASE 1949/1948	REGISTERED 1948 2/	ESTIMATED 1949	PERCENT INCREASE 1949/1948	REGISTERED 1948 2/	ESTIMATED 1949	PERCENT INCREASE 1949/1948
ALABAMA	391,704	425,000	8.5	141,370	151,000	6.8	533,074	576,000	8.1
ARIZONA	161,547	175,000	8.3	49,450	53,000	7.2	210,997	228,000	8.1
ARKANSAS	256,527	270,000	5.3	125,906	135,000	7.2	382,433	405,000	5.9
CALIFORNIA	3,194,226	3,350,000	4.9	554,081	590,000	6.5	3,748,307	3,940,000	5.1
COLORADO	354,748	375,000	5.7	107,588	115,000	6.9	462,336	490,000	6.0
CONNECTICUT	536,867	568,000	5.8	88,612	92,000	3.8	625,479	660,000	5.5
DELAWARE	68,240	72,000	5.5	18,816	20,000	6.3	87,056	92,000	5.7
FLORIDA	616,432	670,000	8.7	154,503	165,000	6.8	770,935	835,000	8.3
GEORGIA	540,984	585,000	8.1	166,833	175,000	4.9	707,817	760,000	7.4
IDAHO	156,979	168,000	7.0	60,590	65,000	7.3	217,569	233,000	7.1
ILLINOIS	1,899,305	2,050,000	7.9	305,761	320,000	4.7	2,205,066	2,370,000	7.5
INDIANA	1,059,447	1,115,000	5.2	236,010	250,000	5.9	1,295,457	1,365,000	5.4
IOWA	734,281	785,000	6.9	152,917	165,000	7.9	887,198	950,000	7.1
KANSAS	570,705	605,000	6.0	179,060	192,000	7.2	749,765	797,000	6.3
KENTUCKY	468,901	505,000	7.7	139,921	150,000	7.2	608,822	655,000	7.6
LOUISIANA	390,663	430,000	10.1	121,926	132,000	8.3	512,589	562,000	9.6
MAINE	187,132	192,000	2.6	61,585	62,000	0.7	248,717	254,000	2.1
MARYLAND	469,500	495,000	5.4	99,582	102,000	2.4	569,082	597,000	4.9
MASSACHUSETTS	943,329	995,000	5.5	155,464	159,000	2.3	1,098,793	1,154,000	5.0
MICHIGAN	1,741,613	1,870,000	7.4	237,716	250,000	5.2	1,979,329	2,120,000	7.1
MINNESOTA	798,144	860,000	7.7	170,334	185,000	8.6	968,478	1,045,000	7.9
MISSISSIPPI	263,239	285,000	8.3	127,735	140,000	9.6	390,974	425,000	8.7
MISSOURI	876,882	915,000	4.3	227,248	240,000	5.6	1,104,130	1,155,000	4.6
MONTANA	145,800	155,000	6.3	69,993	76,000	8.6	215,793	231,000	7.0
NEBRASKA	394,306	410,000	4.0	109,509	115,000	5.0	503,815	525,000	4.2
NEVADA	47,328	50,000	5.6	13,671	14,000	2.4	60,999	64,000	4.9
NEW HAMPSHIRE	119,611	125,000	4.5	37,364	39,000	4.4	156,975	164,000	4.5
NEW JERSEY	1,112,470	1,195,000	7.4	205,249	215,000	4.8	1,317,719	1,410,000	7.0
NEW MEXICO	126,458	140,000	10.7	47,160	51,000	8.1	173,618	191,000	10.0
NEW YORK	2,721,884	2,920,000	7.3	434,007	450,000	3.7	3,155,891	3,370,000	6.8
NORTH CAROLINA	659,725	702,000	6.4	171,981	183,000	6.4	831,706	885,000	6.4
NORTH DAKOTA	162,796	173,000	6.3	70,748	78,000	10.3	233,544	251,000	7.5
OHIO	2,096,623	2,230,000	6.4	299,925	320,000	6.7	2,396,548	2,550,000	6.4
OKLAHOMA	508,318	545,000	7.2	164,922	180,000	9.1	673,240	725,000	7.7
OREGON	448,545	485,000	8.1	116,232	128,000	10.1	564,777	613,000	8.5
PENNSYLVANIA	2,131,326	2,290,000	7.4	411,306	430,000	4.5	2,542,632	2,720,000	7.0
RHODE ISLAND	190,452	201,000	5.5	31,597	33,000	4.4	222,049	234,000	5.4
SOUTH CAROLINA	381,152	408,000	7.0	95,390	103,000	8.0	476,542	511,000	7.2
SOUTH DAKOTA	185,953	199,000	7.0	60,468	68,000	12.5	246,421	267,000	8.4
TENNESSEE	518,604	555,000	7.0	141,736	151,000	6.5	660,340	706,000	6.9
TEXAS	1,774,498	1,910,000	7.6	497,472	525,000	5.5	2,271,970	2,435,000	7.2
UTAH	164,538	177,000	7.6	40,575	43,000	6.0	205,113	220,000	7.3
VERMONT	95,407	98,000	2.7	15,266	16,000	4.8	110,673	114,000	3.0
VIRGINIA	610,301	665,000	9.0	147,996	155,000	4.7	758,297	820,000	8.1
WASHINGTON	623,913	670,000	7.4	147,815	159,000	7.6	771,728	829,000	7.4
WEST VIRGINIA	302,356	317,000	4.8	97,135	102,000	5.0	399,491	419,000	4.9
WISCONSIN	829,100	865,000	4.3	199,050	210,000	5.5	1,028,150	1,075,000	4.6
WYOMING	82,431	90,000	9.2	30,389	33,000	8.6	112,820	123,000	9.0
DISTRICT OF COLUMBIA	146,164	156,000	6.7	20,846	22,000	5.5	167,010	178,000	6.6
TOTAL	33,261,454	35,491,000	6.7	7,360,810	7,807,000	6.1	40,622,264	43,298,000	6.6

1/ THE ESTIMATES ARE FOR THE CALENDAR YEAR 1949 AND ARE BASED ON INFORMATION SUPPLIED BY STATE AUTHORITIES. PUBLICLY-OWNED VEHICLES ARE NOT INCLUDED IN THIS TABLE. THE NUMBER OF VEHICLES OWNED BY FEDERAL, STATE, AND LOCAL GOVERNMENTS IN 1948 WERE AS FOLLOWS:

AUTOMOBILES	136,989
BUSSES	64,123
TRUCKS	327,950
TOTAL	529,062

2/ REGISTRATION PERIODS ENDING NOT EARLIER THAN NOVEMBER 30 AND NOT LATER THAN JANUARY 31 ARE TREATED AS CALENDAR-YEAR PERIODS. IN THOSE STATES WHERE THE REGISTRATION PERIOD IS DEFINITELY REMOVED FROM THE CALENDAR YEAR, REGISTRATION FIGURES ARE GIVEN FOR THE TWELVE CONSECUTIVE MONTHS OF THE CALENDAR YEAR. FOR DETAILS OF 1948 REGISTRATIONS, SEE TABLE MV-1, 1948.

U. S. GOVERNMENT PRINTING OFFICE: 1949

A complete list of the publications of the Bureau of Public Roads, classified according to subject and including the more important articles in Public Roads, may be obtained upon request addressed to Bureau of Public Roads, Washington 25, D. C.

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(See also adjacent column)

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1933, 5 cents.
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Act I.—Uniform Motor-Vehicle Administration, Registration, Certificate of Title, and Antitheft Act. 10 cents.
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Act III.—Uniform Motor-Vehicle Civil Liability Act. 10 cents.
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An Economic and Statistical Analysis of Highway-Construction Expenditures. 15 cents.
Highway Bond Calculations. 10 cents.
Transition Curves for Highways. $1.25.
Highways of History. 25 cents.
Public Land Acquisition for Highway Purposes. 10 cents.
House Document No. 249. Highway Needs of the National Defense. 50 cents.
Highway Practice in the United States of America. 45 cents.
Public Control of Highway Access and Roadside Development (1947 revision). 35 cents.
Tire Wear and Tire Failures on Various Road Surfaces. 10 cents.
Legal Aspects of Controlling Highway Access. 15 cents.
House Document No. 379. Interregional Highways. 75 cents.
Highway Statistics, Summary to 1945. 40 cents.
Highway Statistics, 1945. 35 cents.
Highway Statistics, 1946. 50 cents.
Highway Statistics, 1947. 45 cents.
Principles of Highway Construction as Applied to Airports, Flight Strips, and Other Landing Areas for Aircraft. $1.50.
Federal Legislation and Regulations Relating to Highway Construction. 40 cents.
Manual on Uniform Traffic Control Devices for Streets and Highways. 50 cents.
Specifications for Construction of Roads and Bridges in National Forests and National Parks (FP–41). $1.25.

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ANNUAL REPORTS

(See also adjacent column)

Public Roads Administration Annual Reports:
1943.
1944.
1945.

MISCELLANEOUS PUBLICATIONS

Road Work on Farm Outlets Needs Skill and Right Equipment.
Indexes to Public Roads, volumes 17–23, inclusive.
Bibliography on Highway Lighting.
Bibliography on Highway Safety.
Bibliography on Automobile Parking in the United States.
Express Highways in the United States: a Bibliography.
Bibliography on Land Acquisition for Public Roads.

REPORTS IN COOPERATION WITH UNIVERSITY OF ILLINOIS

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No. 332 . . . Analyses of Skew Slabs.
No. 345 . . . Ultimate Strength of Reinforced Concrete Beams as Related to the Plasticity Ratio of Concrete.
No. 346 . . . Highway Slab-Bridges With Curbs: Laboratory Tests and Proposed Design Method.
No. 363 . . . Study of Slab and Beam Highway Bridges. Part I.
No. 369 . . . Studies of Highway Skew Slab-Bridges with Curbs. Part I: Results of Analyses.
No. 375 . . . Studies of Slab and Beam Highway Bridges. Part II.

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STATUS OF FEDERAL-AID HIGHWAY PROGRAM

AS OF AUGUST 31, 1949

(Thousand Dollars)

STATE	UNPROGRAMMED BALANCES	ACTIVE PROGRAM											
		PROGRAMMED ONLY			PLANS APPROVED, CONSTRUCTION NOT STARTED			CONSTRUCTION UNDER WAY			TOTAL		
		Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles
Alabama	$10,866	$13,159	$6,669	300.2	$3,629	$2,256	154.6	$10,254	$5,596	303.5	$27,042	$14,521	758.3
Arizona	846	3,236	2,289	41.0	968	664	30.8	6,647	4,501	61.8	10,851	7,454	133.6
Arkansas	1,128	14,566	7,789	353.3	5,780	2,818	131.6	13,218	6,618	202.8	33,564	17,225	687.7
California	3,977	25,594	8,224	134.8	6,047	2,574	62.8	36,500	17,900	216.6	68,141	28,698	414.2
Colorado	3,512	4,436	2,482	116.8	2,716	1,723	83.0	11,390	6,658	244.1	18,542	10,863	443.9
Connecticut	1,746	9,399	4,328	17.5	2,207	1,093	3.6	11,272	5,804	22.7	22,878	11,225	43.8
Delaware	2,692	1,361	680	6.8	751	370	10.6	4,103	2,571	30.9	6,215	3,621	48.3
Florida	4,204	18,427	9,725	474.2	2,004	1,035	50.2	7,104	3,043	134.9	27,535	13,803	659.3
Georgia	1,092	19,002	9,877	619.0	15,382	6,639	144.1	33,002	16,663	657.5	67,386	33,179	1,420.6
Idaho	2,830	9,954	6,230	408.5	1,260	711	57.7	4,810	2,962	82.2	16,024	9,903	548.4
Illinois	7,198	47,432	25,798	525.9	32,543	14,134	207.8	51,367	25,765	606.0	131,342	65,697	1,339.7
Indiana	9,563	22,269	10,907	97.0	4,422	2,460	22.6	18,941	10,050	113.2	45,632	23,417	232.8
Iowa	1,910	12,111	5,589	479.9	7,458	3,860	280.5	24,975	11,116	894.5	44,544	20,565	1,654.9
Kansas	2,583	12,682	5,507	1,508.4	6,914	3,394	426.5	20,019	10,315	916.9	39,615	19,216	2,851.8
Kentucky	2,075	13,214	6,645	237.1	6,231	3,123	97.2	15,798	7,960	219.4	35,243	17,728	553.7
Louisiana	3,362	23,478	11,052	260.2	11,193	5,529	65.5	17,428	8,093	155.1	52,099	24,674	480.8
Maine	2,403	5,934	3,276	57.9	1,502	753	16.9	7,486	3,721	59.4	14,922	7,750	134.2
Maryland	914	4,266	2,049	30.7	8,201	2,693	23.1	18,082	9,669	69.9	30,549	14,411	123.7
Massachusetts	14,674	16,541	8,735	40.7	3,099	1,371	8.5	21,325	11,233	49.6	40,965	21,339	98.8
Michigan	3,123	14,204	7,025	438.5	8,555	4,288	146.4	45,985	19,947	393.1	68,744	31,260	978.0
Minnesota	1,630	10,807	5,886	626.3	5,103	2,523	208.8	24,794	12,755	583.7	40,704	21,164	1,418.8
Mississippi	8,406	1,018	469	38.1	2,651	1,294	111.7	17,631	8,960	458.9	21,300	10,723	608.7
Missouri	5,464	28,927	14,574	862.5	11,715	5,336	211.6	28,308	15,044	613.6	68,950	34,954	1,687.7
Montana	4,438	14,101	8,362	544.3	2,090	1,275	70.4	11,850	7,285	254.9	28,041	16,922	869.6
Nebraska	4,681	15,890	8,537	532.5	3,175	1,568	54.1	10,501	5,740	347.3	29,566	15,845	933.9
Nevada	1,015	4,508	3,731	132.9	787	610	19.2	3,859	3,196	80.0	9,154	7,537	232.1
New Hampshire	1,494	5,272	2,621	48.4	724	327	4.5	2,987	1,705	12.3	8,983	4,653	65.2
New Jersey	594	15,742	3,321	38.9	7,437	2,836	5.3	25,742	12,591	29.1	48,921	18,748	73.3
New Mexico	1,919	9,166	5,879	318.7	3,378	2,252	79.0	2,367	1,518	62.2	14,911	9,649	459.9
New York	31,126	58,454	32,305	225.7	25,478	11,926	42.7	88,501	43,820	293.9	172,433	88,051	562.3
North Carolina	4,974	14,773	7,212	414.9	6,987	3,275	141.5	19,323	9,511	416.6	41,083	19,998	973.0
North Dakota	2,627	9,203	4,867	1,390.4	3,175	1,556	287.4	8,929	4,709	516.2	21,307	11,132	2,194.0
Ohio	8,518	52,101	25,602	308.4	5,740	2,732	43.3	50,167	24,830	188.8	108,008	53,164	540.5
Oklahoma	3,337	28,422	11,332	829.7	6,340	3,315	284.4	14,909	7,289	593.6	49,671	21,936	1,707.7
Oregon	990	7,565	4,396	174.4	1,709	911	6.9	10,161	5,231	109.9	19,435	10,538	291.2
Pennsylvania	6,904	18,915	9,444	25.5	27,561	13,964	100.1	70,251	34,974	142.2	116,727	58,382	267.8
Rhode Island	2,588	6,733	3,027	18.7	4,020	1,990	3.9	2,987	1,325	8.0	13,740	6,342	30.6
South Carolina	4,629	3,446	1,853	117.2	2,434	1,200	162.0	9,785	4,932	239.6	15,665	7,985	518.8
South Dakota	1,030	10,967	6,578	1,103.1	1,918	1,343	117.9	10,660	6,338	650.3	23,545	14,259	1,871.3
Tennessee	3,292	9,894	4,875	325.8	6,506	3,151	183.5	21,899	10,981	262.8	38,299	19,007	772.1
Texas	4,894	8,902	4,600	561.8	21,179	6,335	538.5	61,485	29,963	1,169.8	91,566	40,898	2,270.1
Utah	1,274	4,474	3,290	144.0	1,689	1,232	63.9	5,552	4,057	155.4	11,715	8,579	363.3
Vermont	897	3,155	1,252	39.3	804	400	15.4	4,184	2,049	49.5	8,143	3,701	104.2
Virginia	10,277	12,884	6,504	283.6	3,711	1,762	113.1	13,134	6,201	169.4	29,729	14,467	566.1
Washington	1,724	14,562	6,266	152.2	3,618	1,336	56.8	13,025	6,142	98.1	31,205	13,744	307.1
West Virginia	568	15,643	6,369	149.8	2,707	1,796	38.3	11,637	5,720	135.0	29,987	13,485	323.1
Wisconsin	7,863	18,588	9,506	488.2	3,859	1,860	165.7	21,411	10,127	438.3	43,858	21,493	1,092.2
Wyoming	428	2,455	1,617	54.6	1,423	998	73.3	7,662	4,949	301.3	11,540	7,564	429.2
Hawaii	2,294	5,599	2,751	33.6	3,359	1,479	9.3	3,278	1,639	16.0	12,236	5,869	58.9
District of Columbia	202	3,874	2,149	1.3	599	300	.8	14,254	6,886	2.2	18,727	9,335	4.3
Puerto Rico	3,110	8,974	4,047	40.6	2,935	1,345	14.5	7,436	2,582	35.4	19,345	7,974	90.5
TOTAL	213,885	716,279	358,098	16,173.8	305,673	143,315	5,251.8	978,375	493,234	13,868.4	2,000,327	994,647	35,294.0